VOLUME XXXV NUMBER 2

THE

JOURNAL OF GEOLOGY

February-March 1927

GASES OF THE MT. PELÉE LAVAS OF 1902

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ABSTRACT

Five specimens of lava were given a complete chemical analysis. The rock is remarkably uniform in chemical composition and shows no appreciable change as between the old peak (Morne Lacroix) and the fresh lava of 1902. The volatiles prove to be very similar to those obtained from other lavas, with notably greater quantities in the glassy material than in the crystalline.

Water is the chief volatile, averaging about 80 per cent by volume, with carbon dioxide averaging 9 per cent. Next in order follow the halogens and sulphur, with fluorine, because of its small atomic weight, reaching 2 per cent by volume though amounting to only 0.005 per cent of the weight of the rock. If we regard the pumice as perhaps contaminated by ocean spray, the chlorine averages 0.6 per cent by volume and 0.06 per cent by weight of rock. Sulphur and carbon monoxide are about 1 per cent each by volume, with hydrogen showing only 0.3 per cent. Gases of the argon group are present but only to about 0.01 per cent by volume.

Attention is called to the misleading inferences which result from accepting the determinations of water made upon rock powders used in analysis as compared with the water determined by exhausting the rock chips in vacuo. The error may be ten times the actual water or may even reverse the order in a series.

It is shown that the glassy bread-crust surface of a bomb, instead of having lost its volatiles as has been sometimes suggested, has retained them because of the sudden chilling. Gas-charged volcanic glasses are discussed, and the conditions required for the formation of bread-crust surfaces are indicated. The relation of such glasses to the phenomena of the nuées ardentes is discussed. From the volatile content of these glasses as well as from the phenomena of the "spine" it is shown that pressures of the order of at least one hundred atmospheres were probable within the dome during the declining phase of activity.

The first paper of this series[1] discussed in detail the methods of collecting and analyzing gases as well as offering some general considerations pertaining to the problem as a whole. In the course of

[1] E. S. Shepherd, "The Analysis of Gases Obtained from Volcanoes and from Rocks," *Journal of Geology*, Vol. XXXIII (1925), pp. 289–370.

the development work we had opportunity to examine a few specimens from the 1902 eruption of Mt. Pelée, Martinique. Four of the five specimens studied were supplied by the late Dr. E. O. Hovey, and a pumice from one of the lateral nuées ardentes by Professor Lacroix. Anything like a complete study of the rocks of the region was not feasible, so we confined our work mostly to the rocks of this particular eruption. Since it was impossible to collect the gas given off during these explosive eruptions, one is necessarily dependent upon the residual gases still contained in the fresh rock. Our experience with the lavas and gases at Kilauea has satisfied us that this method is reliable enough for our present purpose, and the inferences based upon the residual gases of the fresh rock are quite as instructive as we may hope to obtain. Some fumarole gases from Pelée have been examined, but, as previously pointed out, such gases need bear no particular relation to the magmatic gases.

THE MATERIAL EXAMINED

The petrographic description of these rocks has already been given in great detail by Lacroix and need not be repeated here. The rocks are too fine grained to permit exact mineralogical determination, so that the mode will not be given. Other than to make certain that we were dealing with the same kind of material, we have not repeated Lacroix's studies. All of these specimens are porphyritic hypersthene andesites with phenocrysts about 1 mm. in diameter. Groundmass and phenocrysts are about equal in amount. From 80 to 90 per cent of the phenocrysts are plagioclase ranging from 45 to 80 per cent anorthite, the most calcic material being in much smaller amount in the centers of the grains. Hypersthene is the only other chief mineral of the phenocrysts (β refractive index around 1.715), containing about 30 per cent of iron and manganese, according to Lacroix. The groundmass and other peculiarities will be considered individually.

MP/4. A fragment of Morne Lacroix, the old summit, collected by Hovey. "A piece of the old summit pinnacle of the mountain which rose in and above the eastern rim of the old crater." Groundmass very fine grained but nearly or quite holocrystalline with cavities containing tridymite (Table I).

MP/5. "Fragment of a great block in the eastern portion of the old valley between the old crater wall and new cone of eruption. Evidently part of the spine of 1902–3 before the spine fell to pieces.

TABLE I

MP/4. HYPERSTHENE ANDESITE. A PIECE OF THE OLD SUMMIT PINNACLE OF THE MOUNTAIN (MORNE LACROIX) WHICH ROSE IN AND ABOVE THE EASTERN RIM OF THE OLD CRATER

(Mode: Not accurately determinable. See Lacroix, *op. cit.*)

ROCK ANALYSIS

Constituents	Percentage	Constituents	Percentage
SiO_2	62.05	ZrO_2	0.003
Al_2O_3	17.99	P_2O_5	0.23
Fe_2O_3	2.11	SO_3	.....
FeO	4.13	Cl	0.03
MgO	2.21	F	p.n.d.
CaO	6.48	Cr_2O_3	.....
Na_2O	3.39	MnO	0.14
K_2O	0.97	NiO	.....
H_2O+	0.08	BaO	0.02
H_2O-	0.01	CuO	.....
CO_2	.....		
TiO_2	0.50	Total	100.32

VOLATILES

Constituents	Weight Percentage of Rock	Volume Percentage at 1200° C.	Atomic Percentage	
CO_2	0.01132	8.609	C	3.455
CO	0.00123	1.473	H	54.360
H_2	0.00002	0.199	O	27.016
N_2	0.00201	1.228	N	0.840
A	nd	.....	A	.....
S_2	0.00650	1.732	S	1.186
Cl_2	0.00308	0.934	Cl	0.639
F_2	0.00573	2.575	F	1.763
H_2O	0.08784	83.248	.....	
Total	0.13066 cc./gm. 7.1	99.998	.....	

NORM

Quartz	18.72	Hypersthene	9.06
Orthoclase	6.12	Ilmenite	0.91
Albite	28.82	Magnetite	3.02
Anorthite	30.58	Apatite	0.34
Diopside	2.97		

Symbols: (I)II. 4. 3(4). 4″

I could not determine which side of the block was nearest the original surface, so took block at random March, 1915" (E. O. H.). Groundmass contains pyroxene, feldspar, tridymite, and glass(?). Frag-

TABLE II

MP/5. HYPERSTHENE ANDESITE, MT. PELÉE, MARTINIQUE.
PART OF THE "SPINE" OF 1902–3

(Mode: See Lacroix, *op. cit.*)

ROCK ANALYSIS

Constituents	Percentage	Constituents	Percentage
SiO_2	63.53	SO_3	.....
Al_2O_3	17.02	Cl	0.02
Fe_2O_3	2.80	F	p.n.d.
FeO	3.25	S	0.003
MgO	2.08	Cr_2O_3	none
CaO	5.83	V_2O_3	.....
Na_2O	3.59	MnO	0.14
K_2O	1.05	NiO	.....
H_2O+	0.16	BaO	none
H_2O-	0.09	SrO	.....
CO_2	.....	LiO	.....
TiO_2	0.47	CuO	.....
ZrO_2	0.02		
P_2O_5	0.16	Total	100.22

VOLATILES

Constituents	Weight Percentage of Rock	Volume Percentage at 1200°C	Atomic Percentage
CO_2	0.01782	10.109	C 4.140
CO	0.00225	2.007	H 56.623
H_2	0.00002	0.252	O 35.795
N_2	0.00095	0.854	N 0.581
A	0.00001	0.008	A 0.003
S_2	0.00123	0.480	S 0.331
Cl_2	0.00110	0.387	Cl 0.264
F_2	0.00505	3.317	F 2.263
H_2O	0.05957	82.525	.....
Total	0.08818 cc./gm. 4.8	.....	.....

NORM

Quartz	22.38	Hypersthene	7.57
Orthoclase	6.12	Ilmenite	0.91
Albite	30.39	Magnetite	4.18
Anorthite	27.24	Apatite	0.34
Diopside	0.68		

Symbols: "II. 4. 3". 4"

ments of a highly feldspathic and more coarsely crystalline rock are present. After heating in vacuo much of the groundmass was still partly crystalline and the plagioclase phenocrysts were only partly

TABLE III

MP/6. HYPERSTHENE ANDESITE, MT. PELÉE, MT. MARTINIQUE. SUMMIT OF NEW CONE NEAR EASTERN EDGE OF SPINE OF 1902

ROCK ANALYSIS

Constituents	Percentage	Constituents	Percentage
SiO_2	62.79	SO_3	
Al_2O_3	17.61	Cl	0.02
Fe_2O_3	3.36	F	
FeO	2.66	S	
MgO	1.98	Cr_2O_3	
CaO	6.15	V_2O_3	
Na_2O	3.27	MnO	0.14
K_2O	0.95	NiO	
H_2O+	0.08	BaO	0.02
H_2O-	0.03	SrO	
CO_2		Li_2O	
TiO_2	0.50	Cu	
ZrO_2	0.01		
P_2O_5	0.30	Total	99.88

VOLATILES

Constituents	Weight Percentage of Rock	Volume Percentage at 1200° C.	Atomic Percentage
CO_2	0.02575	20.260	C 7.541
CO	0.00139	1.391	H 49.519
H_2	0.00001	0.185	O 39.219
N_2	0.00249	2.494	N 0.224
A	0.00003	0.023	A 0.078
S_2	0.00437	1.925	S 1.333
Cl_2	0.00398	1.575	Cl 1.097
F_2	0.00192	1.420	F 0.988
H_2O	0.04543	70.726	
Total	0.09145 cc./gm. 4.3		

NORM

Quartz	24.24	Hypersthene	5.82
Orthoclase	6.12	Ilmenite	0.91
Albite	27.25	Magnetite	5.34
Anorthite	28.91	Apatite	0.67
Diopside	0.00		

Symbols: (I)II. 4. 3(4). 4″

dissolved. Hypersthene and magnetite phenocrysts were considerably attacked and surrounded by a very dark glass. Much of the

TABLE IV

MP/1. HYPERSTHENE ANDESITE, MT. PELÉE, MARTINIQUE. PUMICE FROM THE NUÉE ARDENTE, JULY 9, 1902

ROCK ANALYSIS

Constituents	Percentage	Constituents	Percentage
SiO_2	62.51	SO_3	
Al_2O_3	17.56	Cl	0.09
Fe_2O_3	1.94	F	p.n.d.
FeO	4.15	S	0.003
MgO	2.12	Cr_2O_3	
CaO	6.19	V_2O_3	
Na_2O	3.22	MnO	0.14
K_2O	0.98	NiO	
H_2O+	0.60	BaO	0.02
H_2O-	0.08	SrO	
CO_2		Li_2O	
TiO_2	0.50	Cu	
ZrO_2	0.02		
P_2O_5	0.20	Total	100.32

VOLATILES

Constituents	Weight Percentage of Rock	Volume Percentage at 1200° C.	Atomic Percentage
CO_2	0.01614	7.441	C 3.324
CO	0.00173	1.256	H 54.360
H_2	0.00004	0.435	O 27.016
N_2	0.00327	2.371	N 1.809
A	0.00001	0.007	A 0.003
S_2	0.00915	2.892	S 2.208
Cl_2	0.03669	10.495	Cl 8.008
F_2	0.00803	4.289	F 3.272
H_2O	0.06289	70.812	
Total	0.13794 cc./gm. 5.9		

NORM

Quartz	21.42	Hypersthene	10.15
Orthoclase	6.12	Ilmenite	0.91
Albite	27.25	Magnetite	2.78
Anorthite	30.30	Apatite	0.34
Diopside			

Symbols: (I)II. 4. (3)4. 4″

hypersthene was too dark to be transparent in thin section owing in part to the dark glass and in part to very dark or opaque crystals developed in the hypersthene and penetrating dark glass (Table II).

MP/6. "Fragment from summit of new cone as it was in March, 1915. From a ledge in middle, north, and south, near eastern edge of site of spine of 1902" (E.O.H.). The ferromagnesian phenocrysts (probably hypersthene) are surrounded by reaction products of a deep red-brown color having strong birefringence and high refractive index. The same mineral in the form of needles seems to be scattered through the fine grained partly glassy groundmass. Lack of material prevented definite characterization of the mineral (Table III).

MP/1. Pumice, "andesite à hypersthene, type ponceux, nuées ardentes le juillet, 1902" (Lacroix). The cellular glass has few microlites. After heating in vacuo the phenocrysts in some parts of the mass were completely dissolved. Small amounts of hypersthene crystals were filled with a meshwork of glass and imbedded in dark glass, but no distinct reaction border appeared. Magnetite residuals were surrounded by very dark glass. Analysis gave the following results as shown in Table IV.

MP/7. "Shell of bread-crust bomb 1902–3 eruption" (E.O.H.). Phenocrysts in a slightly bubbly light-colored glass (Table V).

Whatever mechanism may be invoked to account for the appearance of the new lava, it must take account of the singular uniformity in chemical composition throughout the eruptive period, and the even more surprising fact that the lava of 1902 is substantially identical in composition with the old peak, Morne Lacroix. In this respect our analyses are in good agreement with the many analyses furnished by Lacroix (Table VI), with the slight correction due to the fact that our results run systematically slightly lower in alumina and higher in silica for the same material. The lack of any appreciable change in the composition of the lava from Pelée is more striking if, instead of percentage compositions, we substitute the molecular numbers ($\times$1,000).

There is a slight variation in the state of the iron where the glassy andesite MP/1 and MP/7 show more ferrous, but this need mean no more than a lesser chance to oxidize. When we recall that MP/4 is the old peak, Morne Lacroix, erupted centuries ago, the unchanged composition as between the old and new lavas is very striking.

In passing we would note that the determination of water made upon the powdered rock bears no predictable relation to the amount

TABLE V

MP/7. Hypersthene Andesite, Mt. Pelée, Martinique.
Glassy Surface of Bread-Crust Bomb, 1902–3

Rock Analysis

Constituents	Percentage	Constituents	Percentage
SiO_2	62.87	SO_3	.....
Al_2O_3	17.35	Cl	0.09
Fe_2O_3	1.54	F	p.n.d.
FeO	4.31	S	0.01
MgO	2.08	Cr_2O_3	.....
CaO	6.05	V_2O_3	.....
Na_2O	3.41	MnO	0.16
K_2O	1.04	NiO	.....
H_2O+	0.42	BaO	0.01
H_2O-	0.00	SrO	.....
CO_2	.....	Li_2O	.....
TiO_2	0.46	CuO	.....
ZrO_2	0.01		
P_2O_5	0.23	Total	100.04

Volatiles

Constituents	Weight Percentage of Rock	Volume Percentage at 1200° C.	Atomic Percentage
CO_2	0.00801	0.824	C 0.352
CO	0.00132	0.214	H 65.070
H_2	0.00019	0.427	O 33.029
N_2	0.00131	0.213	N 0.142
A	tr	.....	A .....
S_2	0.00083	0.063	S 0.041
Cl_2	0.01544	0.991	Cl 0.668
F_2	0.00867	1.038	F 0.700
H_2O	0.38076	96.227	.....
Total	0.41658 cc./gm. 26.5	.....	.....

Norm

Quartz	20.94	Hypersthene	10.51
Orthoclase	6.12	Ilmenite	0.76
Albite	28.82	Magnetite	3.02
Anorthite	28.91	Apatite	0.34
Diopside	0.35		

Symbols: (I)II. 4. 3(4). 4″

of water obtained when the same rock in the form of chips is melted in vacuo. Thus, for the foregoing material, see Table VII.

The importance of the foregoing figures, which are of the same order in all of our determinations, lies in emphasizing the misleading nature of the figures for water as determined upon the powder used for analysis. In the preceding instance one would infer that the

TABLE VI

	Old Peak MP/4	Spine MP/5	New Cone MP/6	Pumice MP/1	Bread-Crust MP/7	L'02*	L/ma
SiO_2	1,034	1,058	1,046	1,042	1,048	1,002	1,031
Al_2O_3	176	167	173	172	170	183	179
Fe_2O_3	13	18	21	12	9	14	13
FeO	57	46	36	57	60	51	60
MgO	55	50	49	50	52	64	68
CaO	116	104	110	111	108	107	113
Na_2O	55	58	52	52	55	52	52
K_2O	11	11	11	11	11	13	12

* Column L'02 is Lacroix's mean for all 1902 lavas. L/ma is Lacroix's mean value for all of the ancient hypersthene andesites from the peak region.

TABLE VII

Total H_2O Percentage by Weight

	MP/5	MP/6	MP/1	MP/7
From powder	0.25	0.11	0.68	0.42
From chips in vacuo	0.06	0.04	0.06	0.38

pumice, MP/1, contained nearly twice as much water as the dense glassy bread-crust surface, MP/7, when it really contains only one-sixth as much. The error due to powdering is unpredictable, since with some materials the rock is partly dehydrated in the pulverization, though usually the powder takes up water.

THE VOLATILES

For convenience in comparison we have grouped the data for volatiles together in Table VIII.

The paper on methods indicated the need of much more extensive data before other than tentative interpretations would be warranted in the matter of sulphur and the halogens as obtained from rocks and lavas. The halogens are given off with relative ease, though the

TABLE VIII

Summary of Volatiles in Mt. Pelée Lavas

	Weight Percentages of Rock										
	CO_2	CO	H_2	N_2	A	SO_2	S_2	Cl_2	F_2	H_2O	Total Percentage of Rock
MP/4	.02219	.00242	.00002	.00210	udt	udt	.00650	.00308	.00573	.08874	.13066
MP/5	.01782	.00225	.00002	.00095	.00001	.00030	.00108	.00110	.00505	.05957	.08818
MP/6	.02575	.00139	.00001	.00249	.00003	.00004	.00435	.00398	.00192	.04543	.09145
MP/1	.01614	.00173	.00004	.00327	.00001	udt	.00915	.03669	.00803	.06289	.13794
MP/7	.00801	.00132	.00019	.00131	tr	.00015	.00076	.01544	.00867	.38076	.41658

	Volume Percentages of Total Volume of Gas at 1200°, 760 mm.										
	CO_2	CO	H_2	N_2	A	SO_2	S_2	Cl_2	F_2	H_2O	Cc. of Gas per Gm. of Rock
MP/4	8.609	1.473	0.199	1.228	udt	udt	1.732	0.934	2.575	83.248	7.1
MP/5	10.109	2.007	0.252	0.854	0.008	0.117	0.422	0.387	3.317	82.525	4.8
MP/6	20.260	1.391	0.185	2.494	0.023	0.017	1.908	1.575	1.420	70.726	4.3
MP/1	7.441	1.256	0.435	2.371	0.007	udt	2.892	10.495	4.289	70.812	5.9
MP/7	0.824	0.214	0.427	0.213	tr	0.010	0.053	0.991	1.038	96.227	26.5

	Atomic Percentages of Total Gas							
	Carbon	Hydrogen	Oxygen	Nitrogen	Argon	Sulphur	Chlorine	Fluorine
MP/4	3.455	57.241	34.876	0.840	udt	1.186	0.639	1.763
MP/5	4.140	56.623	35.795	0.581	0.003	0.331	0.264	0.263
MP/6	7.541	49.519	39.219	0.224	0.078	1.333	1.097	0.988
MP/1	3.324	54.360	27.016	1.809	0.003	2.208	8.008	2.372
MP/7	0.352	65.070	33.029	0.142	tr	0.041	0.668	0.700

evolution is probably not complete. For example, fluorine is not completely driven out of CaF_2 by dry SiO_2 at 1200° C. for several hours. We are necessarily dealing with ill-defined conditions, and the results need not be rigidly quantitative. Since we are working under as uniform conditions as possible, we feel that the relative values may be allowed a tentative significance.

The values for sulphur are erratic, a fact which may be related to a greater solubility, or less ease of evolution from the crystalline than from the glassy state. In some diabase which we have examined large quantities of H_2S and SO_2 were simultaneously evolved when the material was heated in vacuo; a phenomenon which we have not observed in working with the extrusive rocks.

The gases of the argon group are present in discouragingly small amounts in all lavas thus far examined. Argon, etc., amounts to about 1 per cent of the nitrogen obtained and to about one-tenth of 1 per cent of the total fixed gases. We have never obtained enough in working with from one to two hundred grams of lava to warrant more detailed study.

The halogens proved rather more significant. Chlorine is present in appreciably greater quantity in the glassy than in the crystalline lava, the former showing about ten times as much as the crystalline lava. A similar relation was found in the chlorine as determined in the rock analysis. This halogen also predominates over fluorine, as is to be expected.

Fluorine is a protean element with a singular capacity for transient combinations. Perhaps it is because this element is seldom determined that the quantity found in these determinations seems rather surprising. The quantity is not large measured in weight percentages, but it may well be significant that the amount is appreciably greater in the glassy than in the crystalline lava. In fact, the concentration of halogens in the glassy material is what we might expect, since there is evidently a concentration of total volatiles in the glass. The significance of this concentration of volatiles in the glass as one result of crystallization of the magma will be taken up again in discussing the phenomena presented by the eruptions of 1902–3.

Gases other than water constitute a minor part of the total.

At Lacroix's suggestion, Grossmann[1] extracted the gases from two specimens of Pelée lava. While the exact procedure was not given, he speaks of using a combustion tube, and we infer that the temperature of extraction was not above 800° C. If we recompute our figures to the same base, that is, ignore water, the halogens, and sulphur, we obtain the values given in Table IX. One notes first that if we judge by the fixed gases alone, then the holocrystalline material contains more gas per unit of rock than the glassy material. Some of the figures, as for hydrogen, are striking until we recall

TABLE IX

VOLUME PERCENTAGES OF TOTAL FIXED GASES*

	MP/4 Old Summit	MP/5 Spine	MP/6 New Cone	MP/1 Pumice	MP/7 Bread-Crust	ANDESITE DU DOME	PONCE DU 9 JUILLET
CO_2	74.81	76.41	83.20	64.64	46.35	82.09	78.01
CO	12.79	15.52	5.71	10.90	12.03	7.46	11.11
H_2	1.68	1.90	0.76	3.78	24.02	5.02	2.12
N_2	10.67	6.45	10.24	20.61	11.98	5.42	6.61
A	.....	0.06	0.09	0.06	.....	.....	2.20
Cc./100 cc.	37.8	29.9	48.6	22.5	29.2	8.0	2.5

* The last two columns are Grossmann's values.

that the hydrogen of MP/7 (bread-crust) amounted to but 0.4 per cent of the total volatiles. Of course, should local conditions permit the concentration of the hydrogen, as by condensation of the water vapor, then a potent explosive mixture might result, but such effects should be unusual and not a part of the main explosion. Such enrichment in combustible gases doubtless occurs at Vesuvius when the lava is standing at the lower levels in the conduit, since Perret was able to keep track of the rise or fall of the lava column by the explosions at its surface.

It may also be noted that CH_4, which we have not found in our studies, was not found by Grossmann in his, although it is reported in the fumaroles.

Under our conditions of extraction the hydrogen is notably greater in the glassy material—which agrees with the ferrous-ferric relations observed in the analysis of the rock. We obtained considerably

[1] *Comptes rendus*, Vol. CXLVIII (1909), p. 991.

more gas at 1200° than Grossmann below 800° C., as was to be expected, but otherwise we are in fair agreement. Little of value can be read out of the figures as computed in Table IX, beyond what is equally obvious in the complete gas analysis. If Gautier's experiment on the relations between hydrogen, water, and ferrous silicates is sufficient, then we might expect that Grossmann, working at the lower temperature, would find a much higher percentage of hydrogen than we would obtain at 1200°. While the data are too scanty for a conclusion, it appears that in this instance at least the reactions did not work out in that way.

The most significant fact about the Pelée rocks lies in the water content. The holocrystalline material shows what we have come to regard as a normal or usual gas content, something of the order of 7 cc. of total volatiles at 1200° C. for each gram of rock, about 80 per cent of the volatiles being water. The value for the bread-crust MP/7 jumps to 26.5 cc./gm. Thus, at about 1000° C., each cubic meter of issuing lava has at least 50 cubic meters of gas available; this means a minimum partial pressure of fifty atmospheres. We feel justified in assuming that this represents a minimum of gas, since the more highly charged material exploded in the form of ash and lapilli. One would have supposed that the pumice had sufficient opportunity to part with all of its volatiles, but it contains nearly 7 cc./gm. of volatiles, a figure similar to that of the pahoehoe sponge from Hawaii.

BREAD-CRUST BOMBS

Lacroix says: "Lorsqu'une portion du magma à très haute température est projetée dans l'atmosphere à l'état pateux, elle se refroidit brusquement à sa périphérie, expulsant les gaz qu'elle contient; c'est ainsi que prend naissance la croûte obsidiennique."[1] This inference was doubtless based upon the water or "perte" values obtained from the powdered material used in the analyses. The reverse happens to be the fact. The chilled surface has retained a much larger amount of the available gases. Similar results were obtained for the Lassen Peak material.[2] The crust cools before

[1] *Op. cit.*, p. 523. (A. Lacroix, *La Montagne Pelée et ses Eruptions* (Paris, 1904).

[2] A. L. Day and E. T. Allen, "The Volcanic Activity and Hot Springs of Lassen Peak," *Carnegie Institution of Washington Publication No. 360* (Washington, D.C., 1925).

vesiculation gets under way, while in the more slowly cooling interior, vesicles have opportunity to go on forming with swelling which cracks the bomb and turns the edges of the cracks outward. This swelling and evolution of gas continues sometimes for days, in the case of large blocks, ultimately reducing them to piles of detritus which simulate at times small fumaroles. Such large blocks would soon cool below the vesiculation temperature range were it not for the crystallization process which is going on at the same time. Not only does crystallization liberate heat throughout the mass, but by concentrating the volatiles in the remaining hot glass it decreases the viscosity of this glass and simultaneously increases the internal gas pressure.[1] Our specimen of the spine of Pelée is almost holocrystalline, but contains minute ramifying vesicles which give the rock a notably sugary texture. Such a rock, while crystallizing with every pore under very high pressure, might shatter explosively if suddenly erupted into a region of low external pressure.

The conditions under which bread-crusting can occur are very limited. Possibly a temperature change of one hundred degrees or less determines whether a bomb shall develop a bread-crusted surface or completely expand to pumice. None of our specimens showed the type of bread-crusting which very special conditions of reheating produce.

GAS-CHARGED VOLCANIC GLASSES

We have heated obsidian containing 75 per cent SiO_2 and showing 55 cc. of gas per gram (at 1200° C.), the gas being 93 per cent H_2O. At about 850° C. the glass puffs up to pumice. In vacuo and at about the same temperature the glass froths so as to coat the inside of the inclosing silica tube, and in doing so is drawn out into fine threads and rods which become rigid when the gas escapes. These threads do not then give way even when the temperature is raised to 1250° C. The relatively small amount of volatiles (0.9 per cent by weight) renders the glass quite as mobile in the range between 800° and 1000° as it is several hundred degrees higher when freed from volatiles. In studies presented by Day[2] it was found for

[1] George W. Morey, "Development of Pressure in Magmas," *Journal of Washington Academy of Sciences*, Vol. XII (1922), p. 219.

[2] Arthur L. Day and E. T. Allen, *op. cit.*

the Lassen Peak andesite, which was about half glass and contained 10.6 cc./gm. volatiles (0.15 per cent by weight), that no apparent change in outline occurred even on polished surfaces when heated for five hours in a neutral atmosphere at about 780° C. After three hours at 840° C., the glass, which under the microscope was originally brown and cloudy, began to clear, and the surface showed minute warpings. After one and a half hours at 930°-970° C. a long prismatic piece supported only at the ends sagged and swelled appreciably, and the glass became clear. The same material heated for fifteen minutes at 1040° C. flowed under its own weight with decided vesiculation.

The Lassen Peak andesite contains 2 per cent more iron and 2 per cent less alkali than the Peléean and seems rather more easily fusible and less viscous when free from volatiles. The Lassen material studied contained also less volatiles than the bread-crust glass from Pelée. Consequently we must qualify the results of our studies of Lassen material in trying to apply them to the Pelée problems. The indications are that the phenomena observed with the Lassen material would be similar and more intense in the case of Martinique material.

It will be noted that the relationships between temperature, viscosity, volatile content, and pressure[1] are complex. Increased concentration of volatiles implies a reduction in viscosity accompanied by an increased pressure if the temperature remains constant. Increase of temperature implies rise in pressure and decreased viscosity, and vice versa. A crystallizing rock, by concentrating volatiles in the mother-liquor, raises the pressure and lowers the viscosity, with, however, two opposing forces: the increase in viscosity due to lowering temperature and in some cases increased silica content of the mother-liquor. In the glass from such a system Lacroix found 72 per cent of silica as against the mass content of 63 per cent. This implies an appreciable increase in the viscosity of the glass if the glass is not at the same time enriched in volatiles.

It follows from the above considerations that the lava erupted at Pelée should have shown various stages of crystallinity and

[1] Pressure in this connection refers always to the partial pressure of the volatiles in relation to the rock magma in which they are dissolved.

vesiculation. In part[1] it was practically pure glass, some of which exploded to ash, some to pumice, and some found conditions right to produce bread-crust bombs. Other masses were crystallizing at the time of eruption with the groundmass capable of vesiculation or even explosion. Still other portions may have been practically holocrystalline, but with the vesicles under high pressure. With these possibilities in mind, the explosive behavior of the nuées ardentes described by Lacroix is more easily understood.

NUÉES ARDENTES

It will be remembered that there was no permanent opening in the Pelée crater. There was no open conduit in which lava rose and fell as it does at Vesuvius or Kilauea. Instead of there being a conduit, a solid core or plug of lava about 800 meters in diameter was pushed up through the bottom of the old crater, l'Étang Sec. The top of this plug formed the dome along the more active side of which the terminal spine was subsequently forced up. All, more than a hundred, of the nuées ardentes observed by Lacroix originated on the southwest flank of this dome near the junction of the spine with the rocky substratum.

The appearance of a nuée was always heralded by heavy rumblings, often continued for several hours in the case of the larger eruptions. Then a heavy explosion accompanied the forceful ejection laterally of a momentarily glowing mass of lava. The mass began at once to expand into a cloud, so that the duration of the almost momentary blast could not be observed. In a few seconds the cloud occupied a volume many thousand times the volume of the lava at first seen. The cloud rushed down the mountain, often to the sea, a distance of about 6 kilometers, at a rate of from 20 to to 30 miles an hour. Its base followed like a torrent the slightly sinuous valley into the head of which the mass was first projected. The onrushing nuée enlarged vertically much more than laterally, but soon subsided, leaving a sharply outlined white trail and valley-floor covering of ash, pumice, and coarser fragmental material. Some of the larger masses of lava which came down to the sea in the

[1] Lacroix, *op. cit.*

base of the cloud were more than a meter in diameter and pursued the last half of their course over a grade of less than 1:6.

Lacroix says: "A schematic section of such a nuée in motion at some distance from its origin would show: at the base a zone of high temperature in which solid material would predominate (blocks of all sizes, smaller fragments, and fine ash); every part of these solid particles radiates heat and should be surrounded by an atmosphere of gas and vapors extremely compressed at the beginning but expanding rapidly; it is this atmosphere which prevents the solid particles from touching one another, thus maintaining the mass in a state of mobility which enables it to flow down the slopes almost like a liquid." Lacroix showed that explosive and asphyxiating gases were absent, and he believed the gas to be chiefly steam.

Fenner[1] has recognized the necessity for continued almost explosive evolution of gas from the ash in the Valley of Ten Thousand Smokes to account for the gradients there observed, while Perret[2] discusses the nuées ardentes and distinguishes clearly between them and the hot-ash avalanches which he observed on Vesuvius.

It seems that the relation of viscosity to gas content was such that only parts of the masses which issued from the dome at Pelée exploded; the rest broke up into variously sized fragments which intumesced more or less violently during their progress forward. The nuée ardente is thus a self-generating cloud.

To the description and explanations given by Lacroix, Fenner, and others, we are able to add some idea of the gases present and the possible intensity of their evolution. If we assume that the bread-crusted material which we analyzed had less than the maximum original gas content, an assumption justified by the fact that the more highly charged material exploded to form ash, then for each cubic meter of lava there was present at least 70 cubic meters of gas at a pressure of fifty atmospheres at 1200° C. The emulsion of hot blocks and ash was thus possessed of ample energy to keep

[1] Clarence N. Fenner, "The Origin and Mode of Emplacement of the Great Tuff Deposit of the Valley of Ten Thousand Smokes," *National Geographic Society Contributed Technical Papers*, Katmai series, No. 1 (1923).

[2] F. A. Perret, "The Vesuvius Eruption of 1906," *Carnegie Institution of Washington Publication No. 339* (1924).

it well stirred and prevent its coming to rest until the gas evolution had quieted down, that is, until the mass had cooled appreciably. From what is known of the heat-insulating properties of such ash mantles it can be readily understood how the nuées could travel several miles before becoming exhausted.

An approximate figure for the probable pressures within the dome may be computed from the height of the spine. It will be recalled that the spine rose continuously. There were periods of rest, but the spine, according to Lacroix's elaborate observations, did not settle back, but always moved upward if it moved at all. If, then, we assume a free floating spine, an assumption whose errors would give a lower rather than too high a figure, we may compute the pressure in the dome. Assuming an average height of 300 meters, the computation indicates about 100 atmospheres as the probable pressure within the dome. For reasons given previously, we regard the volatiles in the bread-crusted portion of our material as less than maximum, and we found that these volatiles at 1200° corresponded to an internal pressure of about 50 atmospheres. The order of magnitude for the two methods is sufficiently close and justifies the inference that the lava which constituted the explosive portions of the nuées ardentes could exhibit an internal pressure of over 100 atmospheres.

Pressures sufficient to cause volcanic phenomena have been accounted for by Morey[1] and discussed by Day[2] in relation to Lassen Peak. Morey shows how the volatiles liberated during crystallization may generate pressures of several hundred atmospheres.

It is reasonable to suppose that the ultimate cause of pressure at Mt. Pelée was crystallization, but to account for the nuées ardentes requires some mechanism for releasing the pressures a little at a time.

At depth, as the concentration of volatiles proceeds, the pressure produced keeps the volatiles in solution so that bubbles do not form.[3]

[1] *Op. cit.* [2] *Op. cit.*

[3] We have as yet no data which allow us to determine at what depths bubbles can form or are likely to form. However, we may, by making suitable assumptions, compute within certain limits the amount of gas necessary from the figures derived earlier in this paper. If we assume that the gas found in the pumice (about 6 cc. per gm.) represents the solubility at 1200° and one atmosphere for this lava, then at a depth of

Conceivably crystals might grow fast enough to produce supersaturation around their faces and thus induce bubble formation, but the excess pressure would tend to slow down or stop the reaction. It is also conceivable that the concentration of volatiles might become so great that if the external pressure were removed, vesiculation would take place from the exposed surface downward with explosive rapidity. However, to the rapid expansion of a few scattered bubbles a viscous magma must offer resistance comparable to that of a rigid body. Only when vesicles are so numerous that they need expand only a few volumes to make a foam can such concentrations of volatiles as are indicated in the case of the nuées ardentes at Pelée produce explosions.

Before summarizing briefly our concept of the mechanism of the origin of the nuées ardentes at Pelée, of which more than one hundred were observed by Lacroix during about a year and a half, account must be taken of the unusual conditions at the peak. After the initial explosion which destroyed St. Pierre there was no observed crater. Only the dome with its spine existed, and beneath the carapace of the dome the succeeding nuées were brewed. The nuées broke through at a single weak spot in the flank of the dome at the base of the spine. After the outbreak the lowered pressure allowed the sealing of the vent. Also, the lava under the carapace slowly vesiculated deeper and thus built up again pressure sufficient to produce the next eruption.

This gradual transfer of pressure from deeper layers is possible because the viscosity allows these layers to remain supersaturated with volatiles with respect to the lowered pressure under the carapace. This building up of pressures may be independent of, but

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1 kilometer, where the pressure is about 100 atmospheres, it would require about 1,800 cc. per gm. to saturate the magma. This assumes that pressure is the only factor to be considered. Or we may assume that the gas obtained from the chilled surface of the bread-crust bomb represents the solubility of the volatiles at a pressure of 100 atmospheres—the order of pressure within the dome as computed above; then at one kilometer about 75 cc. per gm. would represent saturation and allow the appearance of bubbles. The first assumption may give too high a value, since the pumice may have cooled too rapidly to reach equilibrium, though the specimen examined was from the middle of a nuée and presumably cooled somewhat slowly. The second assumption may give too low a value, since some gas would be lost from the bread-crusted surface in cooling down.

assisted by, whatever crystallization is induced by the slightly lowered temperature or by the lowered content of volatiles in the liquid, both of which phenomena accompany the vesiculation.

For its explosive impetus each eruption depended upon the available mobile vesiculated lava and carried with it material less vesiculated which supplied energy gradually to the cloud after it detached itself from the peak.

SUMMARY

1. Five specimens of lava from Mt. Pelée, Martinique, have been analyzed both chemically and for volatiles.

2. It is shown that in chemical composition these lavas are essentially identical both among themselves and with the old lava of the summit, erupted centuries ago.

3. The volatiles were determined and found to be normal in character and similar to those obtained from the Lassen Peak and Hawaiian lavas, that is, about 80 per cent H_2O.

4. Attention is called to the misleading inferences which result from accepting the determinations of water made upon rock powders used in analysis as compared with the water determined by exhausting the rock chips in vacuo. The error may be ten times the actual water, or even reverse the order in a series. As determined on the powder, the pumice contained ten times as much water as was actually present in the rock and twice as much as the bread-crusted surface of a bomb, whereas the bread-crust really contained six times as much water as the pumice when determined by exhausting the chips in vacuo.

5. Bread-crusting is found to involve not the loss of volatiles, but their retention.

6. The mechanism of the nuées ardentes is clarified by data as to the character and quantities of volatiles present. The approximate pressures involved are computed and shown to be of the order of a hundred atmospheres.

7. The importance of preliminary vesiculation both to the eruption and to the subsequent phenomena of the nuées is indicated.

ESTIMATES OF MARINE AND FLUVIAL EROSION IN HAWAII[1]

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ABSTRACT

The remarkably symmetrical conic surfaces of various parts of Hawaii, now somewhat carved by marine and fluvial agencies, are made the basis of estimates of marine and fluvial erosion. A rate relationship between the two is deduced. Rates of cliff recession appear to be of similar magnitude to those found on the Acadian Coast. Mean depths of fluvial removal range from about 10 feet for the island of Hawaii to about 400 feet for Kauai, the mean for the group being about 100 feet. Total marine erosion for the group is about one-seventh of the fluvial total.

It is concluded that under conditions similar to those of Hawaii marine erosion can approach fluvial erosion in amount only in very early stages of erosion or on islands less than about 10 miles in diameter. Competence of marine erosion to bring about the planation of broad land masses is questioned. Physical evidence indicates a date no earlier than late Tertiary for the first emergence of the Hawaiian volcanic cones as islands in the Pacific Ocean.

INTRODUCTION

Few parts of the earth show such sharp lines between original constructional surfaces and the subsequent destructional surfaces developed by erosion as do volcanic islands like those of the Hawaiian group. The readiness with which the original form of the land may be reconstructed in such islands invites quantitative studies of the relative amounts of marine and fluvial erosion, and these are especially favored by the very fine topographic maps now being issued by the U.S. Geological Survey.

The writer's field studies in Hawaii in 1923 and 1924 have confirmed conclusions suggested by preliminary map studies and established the essential validity of the volumetric measurements of the sort given below. The primary purpose of these measurements was to determine the relative amounts of destruction achieved by marine and subaerial erosion, but it has been possible incidentally to make certain other comparisons which are believed to be of interest to students of land forms.

[1] Published by permission of the director of the Bishop Museum, Honolulu.

The writer's studies in Hawaii were undertaken as Bishop Museum Fellow of Yale University. They were further aided by financial aid and many courtesies from the Hawaiian Pineapple Company. Mr. W. W. Rubey of the U.S. Geological Survey has criticized the manuscript and made a number of helpful suggestions which are here gratefully acknowledged.

METHODS AND ASSUMPTIONS

The validity of certain of the measurements and estimates included in this paper depends on the assumption that the volcanic processes of construction were essentially complete before the slopes of the volcanic cones had been deeply eroded. In a forthcoming paper on the geology and water resources of the Kau district on the island of Hawaii, H. T. Stearns has described deep-buried valleys on the southeast flanks of Mauna Loa which were cut before the younger lava of this district was erupted and which are now filled by the material of these later flows. This rugged ancient topography which is now buried by later flows had a local relief of at least 2,000 feet. If unconformities of this magnitude were general throughout the Hawaiian Islands, the problem which is taken up in this paper would be very much complicated and could not be considered without extensive field work. So far as known to the writer, the greater part of the lava masses of the islands consist of thin flows laid accordantly one on another with but very little evidence of erosion between the formation of successive flows. There are many places on Oahu, Molokai, Lanai, and Kahoolawe where sections of several hundred feet in height and 1 or 2 miles in length may be viewed from one point, and there are a few places such as the north coast of the island of Molokai where one may view in a few hours an almost complete bare cross-section of large parts of a single island. In most of these exposures unconformities which transgress more than one or two flows of 10 feet in thickness are extremely rare and in many parts of these islands are conspicuously absent. The more common sort are those formed by the original lateral margins of single flows rather than by erosion. The writer has not visited Kauai or Niihau or any part of Maui except the immediate coastal surroundings of Lahaina. The presence of buried valleys filled with alluvium has

been recognized on Oahu by Palmer[1] and others, but these are not, so far as known, filled by younger lavas and do not represent erosion of cones older than those of the present exposed topography. It is the writer's impression from casual views of the sea-cliff exposures of northeast Hawaii that erosional unconformities are somewhat more abundant here than in the lavas of Molokai and Lanai, but even here they do not seem to be of sufficient volumetric importance to vitiate the estimates presented in this paper. It is apparent that enormous time intervals are represented by the discordance between the lavas of distinct cones such as those of Kohala and Mauna Kea on Hawaii, or of East and West Molokai; but these major discordances are not involved in the present discussion.

The areas chosen for careful measurement are believed to be simple unit masses of single cones and are not known to include buried, previously dissected masses of old cones. Such dissected and buried masses of old cones are known to exist in the Kau district of Hawaii but, so far as known to the writer, have not been described from other islands. There is no reason for supposing that those on Hawaii represent greater age than some of the exposed topography of Oahu or Kauai. If such ancient and dissected masses should be found on these latter islands buried under lava cones now themselves deeply eroded and representing great age, the suggested physical history of the islands would be greatly extended; but in the lack of such evidence it is thought that the essential point of view of the present paper is valid.

The general mode of attack was to compute the existing volumes of certain volcanic cones or segments of cones and compare these with volumes of the same cones or segments as reconstructed to their original undissected forms. The volumes of both the simple undissected cones and the crenulate dissected cones were computed by measuring the areas contained within certain contours, usually at 500- or 1,000-foot intervals, and computing the volumes by a graphic application of the prismoidal formula as described elsewhere by the writer.[2] In the reconstruction of the original cones from the dis-

[1] H. S. Palmer, personal communication.

[2] C. K. Wentworth, "Graphic Computation of Prismoidal Volumes," *Amer. Jour. Sci.*, 5th Ser., Vol. XI (1926), pp. 305–11.

sected cones, a conservative policy was followed, and there was included within the smoothed contour an area only slightly larger than that contained in a polygonal contour running tangent to the contour margins on successive flow-slope spurs. It is apparent that in such work a personal equation is involved and no two students would derive precisely the same figures on a given measurement. It is believed, however, that in the areas chosen for measurement the interpretation is sufficiently definite so that two observers would not differ by more than 10 per cent in the resulting computed volumes.

Measurements of contour areas were made with a small polar planimeter. A test of its performance showed a maximum deviation of 0.29 per cent from the mean of ten measurements of a typical crenulate area and a probable error of any single measurement of 0.12 per cent. It is apparent that instrumental errors are negligibly small compared to other types of errors.

Volumes removed by marine erosion were computed as follows: The mean height of sea cliff was found by averaging the heights found at several equispaced points along the section of coast in question. The slope in feet per mile of the original conic surface immediately landward of the cliff was taken at a number of points and likewise averaged. The slope of the submarine bench was assumed to average 300 feet to the mile; a value thought to be conservative from an inspection of soundings on Coast and Geodetic Survey charts. The intersection of the subaerial cone slope with the submarine bench slope is situated at a distance from the foot of the cliff which may be found by the following formula, when D is the distance from the cliff foot, H the cliff height and S_c and S_b the cone and bench slopes, respectively:

$$D=\frac{H}{S_c-S_b}$$

As stated above, S_b was taken at 300 feet to the mile, and H and S_c determined in each case by averaging several measurements. The volume contained in the wedge bounded by the cone and bench slopes and the cliff face is given by the following formula:

$$V=\frac{D(H)L}{2}$$

when L is the length of the section in miles. If H is in feet, S_c and S_b in feet per mile, D will be in miles; and correspondingly in the latter formula V will be in mile-feet.[1]

All volumes were computed on the assumption of conic or polyconic forms. In all cases actual contour areas were used and no attempt was made either to deduce or apply laws of ideal form for volcanic cones.[2] Though no attempt was made to test Becker's law of logarithmic form, it is not believed that the major Hawaiian cones would conform to it since their slopes appear too generally to be equilibrium flow angles for molten basalt. It is not improbable that the forms of some of the pyroclastic craters of Oahu would agree closely with the logarithmic form. In a few instances where erosion had removed crests, the summit portions of cones were reconstructed to a few hundred feet higher than any existing remnants, by extrapolating the original surfaces upward. Additional volumes resulting from this procedure were relatively small and no essential difference would be made in the data by omitting this reconstruction. In most instances measurements were continued to the summits of cones or cone segments, but this was not practicable in all cases. Where only a part of the lower slope was measured, the amounts of marine and fluvial erosion were made comparable by dividing the volume removed by streams by the area measured, and making the comparison between average depth of cutting by streams and mile-feet per mile of removal along coasts. There are appreciable differences between the intensities of erosion at different heights on the cone slopes, but these can be neglected in general studies like the present one.

To the estimate of marine and fluvial erosion of the islands as a whole there has been applied the method of random sampling. Lack of topographic maps for some of the islands and economy of time have prevented detailed measurements for the entire area of most of the islands. The methods used in deriving the average figure for a given island may be illustrated by the procedure used for the island

[1] A unit of volume equivalent to the filling of a square mile to a depth of 1 foot.

[2] G. F. Becker, "The Geometrical Form of Volcanic Cones and the Elastic Limit of Lava," *Amer. Jour. Sci.*, 3d Ser., Vol. XXX (1885), pp. 283–93. (Earlier papers by Milne are cited by Becker.)

of Molokai. Careful measurements of contours by the methods outlined above were made for three districts.

A. District including Pelekunu and Wailau gulches extending from the north coast between Haupu Bay and Kalaemilo to the topographic crest between Pepeopae and Puu Ohelo. Area, 16.85 miles. Mean depth of removal, 1,920 feet.

B. District extending along the south coast of Molokai from 3 miles west of Kamalo eastward to Kainalu gulch and inland to the east-west crest of the island. Area, 30.4 miles. Mean depth of removal, 133 feet.

C. District extending from west of Onopalani gulch along the south coast eastward to a point east of Punakou and extending inland to the summit crest of Mauna Loa. Area, 10.90 miles. Mean depth of removal, 48 feet.

By using these areas as bases of comparison and by simple visual inspection the quantities of total fluvial dissection were estimated (see Table I).

TABLE I

TOTAL FLUVIAL DISSECTION OF ISLAND OF MOLOKAI

District	Depth of Removal (Feet)	Area (Square Miles)	Mile-Feet in Volume Removed (Thousands)
East, southeast, south, and southwest slopes of East Molokai	110	120	13.2
Pelekunu-Wailau	1,920	17	32.64
Waikolu and other districts marginal to foregoing	1,000	12	12.
West Molokai and saddle of Mahana constituting remainder of island	20	112	2.24
Average	230	.....	.....
Total	.....	261	60.08

Other islands of the group were estimated in this fashion or by measurement of contours as indicated in the tables below. Estimates of this sort are thought to be within 25 or 30 per cent of the true values in the case of islands which have been mapped in detail.

The mean height of sea cliff round the entire Hawaiian shoreline was estimated by averaging the heights found at all intersections with 5-minute parallels or meridians. Mean slopes of the cones were found in a similar manner, and mean values of the wedge cross-sections were derived from these two values. It was necessary to

exercise personal judgment in recognizing actual sea cliffs, and the disposition of doubtful cases is indicated in the tables.

Practically all computations were made on a 10-inch slide rule and are correct to about $\frac{1}{1000}$, an accuracy thought to be far greater than that of the basic data.

ESTIMATES OF EROSION ON VARIOUS ISLANDS

LOCAL COMPARISONS BETWEEN MARINE AND FLUVIAL EROSION

In the comparisons and discussion which follows, an essential assumption is that the fluvial and marine erosion of the several masses considered has commenced for each at the same time. Were

TABLE II

RELATIVE MARINE AND FLUVIAL EROSION FOR CERTAIN LOCALITIES IN HAWAII

Segment	Area (Square Miles)	Mean Elevation (Feet)	Mean Distance from Sea (Miles)	Slope (Feet per Mile)	Volume Removed by Streams (Mile-Feet in Thousands)	Depths of Removal by Streams (Feet)	Height of Cliff (Feet)	Volume of Marine Removal (Mile-Feet in Thousands)	Volume per Mile of Coast (Mile-Feet in Thousands)	Volume of Marine Removal per Mile of Coast per Foot of Fluvial Removal
1.....	56.0	1,187	3.55	334	20.6	368.0	972	10.9	1.211	.0033
2.....	13.8	1,041	1.15	905	.21	15.1	271	.58	.096	.0064
3.....	31.2	1,332	2.44	546	.115	3.7	173	.59	.084	.0227
4.....	9.0	859	.76	1,130	.064	7.2	232	.205	.051	.0071
5.....	30.0	1,775	2.80	633	.059	2.0	153	.200	.033	.0165

the work of the sea to take place at different levels at different times while fluvial work was continuous in the same channels, the entire study would be vitiated. With the exception of a slight shift of sea-level downward a few thousand years ago[1] by an amount too small to seriously alter the conditions and results of erosion, marine and fluvial erosion on all the islands except Kauai and Oahu are believed to have commenced together in the present cycle and to have continued without serious break to the present. The history of Oahu and probably of Kauai is more complex, but it is impracticable here to attempt specific exceptions for these islands.

[1] C. K. Wentworth and H. S. Palmer, "Eustatic Bench of Islands of the North Pacific," *Bull. Geol. Soc. Amer.*, Vol. XXXVI (1925), pp. 521–44.

Direct comparisons between marine and fluvial erosion were made in five areas as follows:

1. Waipio segment of Kohala cone contained between coast points Long. 155°35¼′ and 155°20′ W. and extending to the Kohala crest.

2. North Hilo segment of Mauna Kea cone contained between Long. 155°15¼′ and 155°20′ W. and extending inland to about 1,750 feet elevation.

3. Hakalau Bay segment of Mauna Kea cone contained between Lat. 19°57½′ and 19°53′ N. on the coast and extending inland to the 2,500-foot contour.

4. Lanai west coast segment extending for 4 miles north from Lat. 20°49′ N. and inland to about 1,500 feet elevation.

5. Hamakua segment of Mauna Kea cone contained between Long. 155°22¼′ and 155°27′ W. and extending inland to the 3,000-foot contour.

For these five areas there is a fairly systematic relationship between the depth of removal by streams and the height of the sea cliff as shown in the following empirical formula, where D is depth of removal and H is height of cliff:

$$D=2\left(\frac{H}{152}\right)^{2.82}$$

Table III shows the agreement between values of depth of fluvial removal actually found and those computed from this formula.

TABLE III

ACTUAL AND COMPUTED DEPTHS OF REMOVAL AS RELATED TO HEIGHT OF MARINE CLIFF

CLIFF HEIGHT (FEET)	DEPTH OF REMOVAL (FEET)	
	Actual	Computed
153	2.0	1.95
173	3.7	2.95
232	7.2	6.56
271	15.1	10.22
972	368.0	374.00

Since in general the height of the cliff is proportional to the square root of the amount of material removed by marine erosion, the formula may be revised to read:

$$D=K(V)^{1.41}$$

and K in this instance is 0.000086 approximately. This means that the total quantity of fluvial erosion increases at least for a long period at a rate nearly midway between the first and second power of the corresponding quantity of marine erosion.

On theoretical grounds it is to be suspected that the rate of fluvial removal increases and that of marine removal decreases with time, at least each relatively to the other. Since the total quantities increase in the ratio stated, the ratio between the two rates must increase very much more rapidly. These figures represent, for the most part, maximum vigor of marine work. On many coasts erosion does not keep pace with the delivery of débris from the land by streams. A comparison of total stream work with total marine work is given below.

It is interesting to apply the formula derived above to the Wailau-Pelekunu district of North Molokai. Here the mean cliff height was found to be 2,210 feet. Substituting in the formula the depth of stream removal was derived as 3,820 feet. The actual value by measurement was 1,920. This is 100 per cent deviation of the estimate from the actual value. However, this case involves an extrapolation far beyond the data from which the formula was established, and one is surprised to find the agreement so close. Stated in the reverse terms: The cliff height corresponding to the depth of removal of 1,920 feet according to the formula is 1,740 feet, only about 21 per cent less than the actual. This is of interest as bearing on the question of whether the North Molokai *pali*[1] is the result of erosion alone or in part of faulting. It is apparent in the case of the Wailau-Pelekunu district that the great depth to which stream valleys have been cut is intimately connected with the high average height of the existing land mass and its proximity to the sea, and that the progress of marine transgression, whether by erosion alone or by the aid of faulting, is an important factor in the augmentation of stream work. This same factor is operative in the five areas measured and reported in Table II, and its effects are included in constants of the formula so that the latter should be applicable to erosional work on the Molokai Coast.

Quite different results are obtained from consideration of the

[1] Hawaiian word meaning cliff.

Pali Kaholo cliff of southwest Lanai. This cliff has a mean height of about 600 feet for a distance of 3 miles. Such a height would correspond to a depth of stream removal of 98 feet. It is apparent from inspection of the map that no such removal has taken place; even the much more dissected Lanai Coast segment measured as area 4 of Table II shows a removal of but 7.2 feet and that of the Pali Kaholo district is probably less than 2 feet, corresponding to a cliff height of 152 feet. Pali Kaholo is thought from other considerations to be a fault scarp, and the very large discordance between the cliff height and stream erosion shown above substantiates this view.

If the relation between fluvial erosion and marine erosion as shown by the empirical formula

$$D = 2\left(\frac{H}{152}\right)^{2.82}$$

is assumed to be correct and the rate of fluvial erosion is taken as constant at 1 foot in 5,000 years, some interesting rates of recession may be worked out for comparison with those quoted by Johnson for parts of the Acadian Coast.[1]

These are shown in Table IV, column 4:

TABLE IV

Segment (see Table II)	Duration of Fluvial Erosion (Years)	Height of Cliff (Feet)	Rate of Recession at 100-Foot Cliff Stage (Feet per Annum)
1	1,840,000	972	.19
2	75,500	271	.28
3	18,500	173	.24
4	36,000	232	.21
5	10,000	153	.20

Rates of marine recession for cliffs averaging somewhat less than 100 feet in height, and in weak rocks on certain parts of the Acadian Coast of the North Atlantic, average somewhat less than 1 foot per year according to a number of figures given by Johnson.[2] Those

[1] D. W. Johnson, *New England Acadian Shoreline* (New York, 1925), pp. 318–30.

[2] *Op. cit.*, pp. 318–30.

developed in Table IV for *100-foot cliffs* and based on a subaerial land erosion rate of 1 foot in 5,000 years average about .22 feet per year. It must be borne in mind that the agreement shown in the five instances given in the table under the first assumption is entirely fictitious for the present purpose and as produced by the constants of the equation used as the primary assumption. It is further to be remembered that the rate of .22 feet depends on the assumed 5,000-year rate. However, the Hawaiian rocks are probably more resistant than those described by Johnson, and it is suspected that the rates of cliff recession deduced above are not more than 100 per cent in error and that no greater error is involved in the assumed 5,000-year rate for one foot of land reduction.

GENERAL PROGRESS OF STREAM EROSION

In Table V are shown the estimated depths of stream removal for several islands.

Though the figures given in Table V differ very greatly in accuracy—and some probably are considerably in error—it is thought that the average depth of removal of 96 feet as derived for the entire group is within 25 per cent of the truth. Several cones, or parts of cones, such as Kauai, the Wainae range, East Molokai, West Maui, and the Waipio district show depth removal as computed or estimated of between 300 and 500 feet. It is possible that this figure represents roughly the limit beyond which it is usually impossible to estimate the amount of reduction. No other district in Hawaii is so situated to show a demonstrable reduction approaching the depth of 1,920 feet shown by the Wailau-Pelekunu district of North Molokai. If other parts of the existing land masses have been so reduced, the fact is not demonstrable from available maps or the writer's personal knowledge of the region. Certain districts such as the southwest part of the Waianae Range and the northeast part of the Koolau Range are so broken down by erosion or faulting or both that their reconstruction is impracticable without careful structural studies in the field. On the other hand, a fine example of a much dissected but still easily reconstructed mass is the magnificent cone of West Maui, of which the complete map has recently been published by the U.S. Geological Survey.

QUANTITIES OF MARINE EROSION

In Table VI are shown estimates and measurements of the cliff heights and volumes removed by marine erosion in Hawaii. Since the volume removed corresponds to the square of the cliff height

TABLE V

FLUVIAL DISSECTION DATA ON HAWAIIAN ISLANDS

Island		Area (Square Miles)	Depth of Removal (Feet)	Volume Removed (Mile-Feet in 1,000's)
Kauai		547	418*	229.0
Niihau		97	20†	1.9
Oahu	Waianae	198	500‡	.....
	Koolau	400	251§	.....
	Total	598	333	199.0
Molokai	West	112	20	.....
	East	149	388	.....
	Total	261	230§	60.0
Lanai		141	25§	3.5
Maui	West	157	385**	.....
	East	571	50††	.....
	Total	728	122	89.0
Kahoolawe		69	15†	1.0
Hawaii	Kohala to Waipio district	625	3	.....
	Hilo (ex. above)	80	370	.....
	Remainder	3,310	1	.....
	Total	4,015	8.7††	35.0
Total		6,456	.....	618.4
Average		.....	96.0	.....

* Complete measurement on small scale map.
† Rough estimate by comparison with islands of similar size and elevation.
‡ Rough comparison with other measured parts of Oahu, very conservative.
§ Part of area measured on large scale map; rest by comparison.
** Complete measurement on large scale map.
†† Rough estimate by comparison with similar measured areas.

the appropriate volume-mean cliff height from which to compute total volumes by multiplication is the square root of the averaged squares of cliff heights taken at uniform intervals. These are given in column 3 under the caption Volume-Mean Cliff Height.

Exclusion of the larger part of the North Molokai removal as due possibly to faulting seems justified since it bears so large a ratio to

the whole. Including it in entirety would increase the total for all Hawaii by about 200 per cent. Taking the figures as compiled it

TABLE VI

DATA ON MARINE EROSION OF HAWAIIAN ISLANDS

Island	Averate Cliff Height (Feet)	Volume-Mean Cliff Height (Feet)	Coastal Perimeter (Miles)	Volume of Erosion in Thousands of Mile-Feet
Kauai*	.....	300	89	11.4
Niihau*	.....	200	46	2.6
Oahu*	.....	100	126	1.8
Molokai†	179	272	92	9.7
Lanai‡	140	147	49	1.5
Maui	52	98	136	1.9
Kahoolawe*	.....	200	33	1.9
Hawaii	191	357	302	55.9
Total	.....	.....	873	85.8

* Cliff heights estimated in round numbers by comparison with other islands.

† Allowing only a uniform maximum cliff height of 500 feet for the North Molokai Coast as due to marine erosion.

‡ Exclusive of the Pali Kaholo cliff which is believed to be due to faulting.

TABLE VII

SUMMARY OF DATA ON FLUVIAL AND MARINE EROSION

Island	Area (Square Miles)	Quantity of Fluvial Erosion (Mile-Feet in Thousands)	Quantity of Marine Erosion (Mile-Feet in Thousands)	Depth of Fluvial Erosion (Feet)	Height of Volume-Mean Sea Cliff (Feet)
Kauai	547	229.0	11.4	418	300
Niihau	97	1.9	2.6	20	200
Oahu	598	199.0	1.8*	333	100
Molokai	261	60.0	9.7	230	272
Lanai	141	3.5	1.5	25	147
Maui	728	89.0	1.9†	122	98
Kahoolawe	69	1.0	1.9	15	200
Hawaii	4,015	35.0	55	8.7	357
Total	6,456	618.0	86	.....	.....
Average	.....	.....	.....	96	262

* The history of Oahu has been more complex than that of most of the other islands, and it is probable that the present estimate of apparent marine erosion includes only a fraction of that which has taken place.

† This value seems low and may well be increased when maps for the whole island are available.

appears that the volume-mean cliff height for all Hawaii is 262 feet. This corresponds to a subaerial removal of about 9.3 feet according to the formula derived above (p. 120). The actual amount as shown

in Table V is 96 feet, which would correspond, using the formula in reverse direction, to about 600 feet of cliff height. It is apparent for the islands as a whole that fluvial erosion bears a far larger ratio to marine erosion than it does in the five selected localities reported in Table II.

DISCUSSION AND CONCLUSION

The two principal factors involved in the ratio between total quantities of fluvial and marine erosion appear, aside from the inherent relative vigor of the two processes under existing climatic conditions, to be the relative age of the land mass in question and its size. The ratio of fluvial work as compared to marine work will increase directly with increase in the linear dimensions of the land mass. In the formula given on page 124 it is suggested that total fluvial work increases at a rate nearly midway between the first and second powers of the total marine erosion. The disparity between the result given by this formula and actual ones for all Hawaii suggests that for land masses advanced somewhat beyond the youthful stage the total fluvial erosion will correspond to a higher power of the marine erosion than the approximate value 1.5 suggested on page 124; perhaps as high as 2 or 2.5. This conclusion corresponds to land masses having about 7.5 square miles of area for each mile of coastal perimeter, or to a circular island of about 30 miles in diameter, instead of about 18 miles in diameter as for the formula.

Because of the differing and unknown ages of the several islands an attempt to work out a detailed relation between area and the fluvial-marine ratio seems unlikely to yield valid results.

From the various considerations enumerated above it appears that for land masses of sizes greater than perhaps 10 miles in diameter, of climatic situation and mean declivity comparable to those of the Hawaiian group, the fluvial erosion is exceeded in amount by marine erosion only in the case of very young islands, such as the island of Hawaii; and tends throughout a large part of the erosion cycle to increase very much more rapidly than the marine erosion, assuming values of one or several score greater for such islands as Kauai and Oahu which are still in a mature stage of erosion. In the case of smaller islands marine erosion is relatively more impressive, involving, because of the lesser height of these cones, the added fac-

tor of more feeble stream erosion due to the greatly reduced mean rainfall.

As the reduction of a land area reaches an advanced stage, fluvial erosion will again reach a low rate which may be exceeded by the rate of marine erosion. It is apparent that marine erosion can accomplish reduction of a land area to lower levels than fluvial erosion by the amount that "wave base" is lower for a given time and place than is existing "grade." Approach to the ultimate level of each of these is exceedingly slow. Reduction of a land mass to low grades is, in the early stages of marine erosion, a considerable aid to the latter process. With the transgression of the sea over much of the land and the development of a broad wave-cut bench, the impediment to farther advance becomes very great, and it is probable that the impediment offered by a broad wave-cut bench will be far greater than that offered by elevated land masses adjacent to the sea. Therefore, the writer questions whether the factor of previous subaerial land reduction is of such importance in favoring extensive marine plantation as some have supposed.

Moreover, the great preponderance of fluvial over marine erosion as a factor in reduction, even of islands such as the Hawaiian group where marine work is at its greatest relative potency, leads him to be somewhat skeptical as to the competence of marine erosion in bringing about the planation of broad land masses, either high or low initially. No impression gained by the student of land forms is more vivid than that of the vigor and intensity of the attack of the sea on the land as voiced by many writers and with especial force by Clarke;[1] but it must be remembered, on the other hand, that marine attack is confined to a total area of the order of $\frac{1}{100}$ or $\frac{1}{1000}$ part of that affected by stream erosion and that in spite of its prodigious power in the immediate coastal zone, the total effects appear to be enormously less than the effect of subaerial erosion.

In considering the bearing of the depth of subaerial erosion on the age of the Hawaiian Islands, there is little purpose in dealing with the average depth of 96 feet, since the ages of the several islands differ greatly. As would be suspected, the islands of Kauai and Oahu show the greatest depths of removal, and Hawaii the least,

[1] Quoted by D. W. Johnson, *op. cit.*, pp. 173–76.

with Maui and Molokai showing intermediate values. The smaller islands of Niihau, Lanai, and Kahoolawe have been eroded much less deeply, more because of their lesser elevations and lesser rainfall than because of lesser age than adjacent large islands. The range of depths of removal is from less than 10 feet for Hawaii to more than 400 feet for Kauai. Little is known of rates of erosion in situations of this sort, and for broad continental areas only the composite net amounts of land reduction are known from the sediments discharged by such rivers as the Mississippi. Various rates of continental reduction have been deduced, but that of 1 foot in 10,000 years is a conservative one. The writer estimated a present rate of reduction of 1 foot in 2,900 years for the island of Lanai and a probable past rate of 1 foot in 5,000 years.[1] On the basis of this rate, the existing topography of Kauai suggests an age of 2,090,000 years. An average depth of removal for the windward part of the Kohala cone of Hawaii of approximately 45 feet corresponds to an age of 225,000 years. In the case of cones which have been actively growing within the past few hundred or thousand years, such as Mauna Kea, Mauna Loa, or Haleakala, the existing amount of dissection is of slight bearing on the age of the cone since growth keeps pace with and obliterates the effects of erosion.

On the island of Oahu certain old terrace gravels are thought to be possibly contemporaneous with one of the Pleistocene glacial invasions on the continental areas. These can hardly be less than 50,000 years old if of Wisconsin age, and may be much older. From the relations of these and associated secondary pyroclastic craters, it is known that the Koolau Range of Oaku had been deeply dissected and cut away by the sea to form a line of sea cliffs averaging perhaps 100 feet high on the leeward side. The dissection is more impressive than the sea-cliff height, since the latter, at least on a windward coast, would correspond to a dissection of not over a foot or two of removal. The discrepancy may be explained by the fact that fluvial erosion has gone on continuously on land while the work of waves has taken place at many levels, many of them now buried beneath the coral and gravel deposits revealed by deep drilling in

[1] C. K. Wentworth, "Geology of Lanai," *Bishop Museum Bull. 24* (1925), pp. 56–57.

and around the city of Honolulu. Too little is known of these features to warrant detailed interpretation here.

From the relations of the supposed Wisconsin or pre-Wisconsin gravels to the much dissected Koolau Range which they flank, it seems clear that the dissection of the range must have taken many times as long as all subsequent time, the latter being at least 50,000 years. The Koolau Range can hardly be much less than 1,000,000 years old on this basis. The duration of the Pleistocene is not known, but according to the views of students of glaciation, may well be one or several million years. It appears likely to the writer, on physical grounds, that the present topography of the older islands represents an early Pleistocene or perhaps late Tertiary beginning. If older land masses formed the nucleus for the cones out of which the present landscape has been wrought, no trace of them has been identified. To the present writer physical evidence does not appear to indicate the emergence of any part of the Hawaiian group above sea-level before the later part of the Tertiary period.

FIRE AS AN AGENT IN ROCK WEATHERING[1]

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ABSTRACT

In the semi-arid, forested mountains of western United States, fire seems to rank first in causing the disruption of bowlders and rock outcrops. This paper contains the result of experiments on the sudden heating of rocks, and considers the field evidence regarding this and related aspects of weathering.

Under the comprehensive term "weathering" are generally included those processes whereby rocks disintegrate or decay at or near the surface of the earth. The best-known agents involved in this complex of processes are ground water and rain acting chemically, bacteria and other micro-organisms, frost, and the roots of plants.

Most writers on the subject of rock weathering either do not mention fire as one of these agents or else accord it only passing mention. Although the action of fire upon building stones is well understood[2] by engineers and insurance specialists, it is commonly supposed that its effect upon rocks in nature is of only minor consequence. It is the purpose of this paper to show that, on the contrary, fire is in some regions very important; and, under suitable conditions, it overshadows all the other factors combined.

In wooded regions of low or moderate rainfall, such as the forest belt of pine and spruce (Hudsonian and Canadian life-zones) in the Rocky Mountains of the United States and Canada, vast areas have been ravaged by forest fires. These have occurred not only in the last century, during the occupation by white men, but for many centuries before. The evidence for this is readily observable in the field,

[1] An abstract of this paper appeared in *Bulletin Geological Society of America*, Vol. XXXVII (1926), p. 142.

[2] E. R. Buckley, "Building and Ornamental Stones." *Wisconsin Geological and Natural History Survey Bulletin IV* (1898), pp. 385–88.

and is too abundant to need exposition in this place. Indians may have started some of these fires, but lightning has doubtless been an important cause. Rock outcrops and bowlders, over thousands of square miles, have thus been subjected to the well-known shattering action of fire, not merely once, but many times.

The characteristic effect of fire upon a rock mass is to expand the outer parts so suddenly that the tensile strength of the rock is exceeded radially and fractures are formed more or less parallel to

FIG. 1.—Large bowlder of quartzite on a glacial moraine in the Medicine Bow Mountains of Wyoming. The effects of fire are seen on the bowlder as well as on the surrounding forest.

the surface. Curved wedges, plates, or scales thus break off and leave a more rounded core, to be attacked in turn by the next fire. These spalls are commonly 1 to 5 centimeters thick, and many of them taper to a thin edge. Such hard undecayed spalls are not to be confused with the crumbly discolored shells that are produced by chemical changes such as hydration, a process to which the term "exfoliation"[1] is usually applied. It seems clear that some observers have mistaken the action of fire for that of insolation, or daily change in temperature.

In rocks that are not homogeneous, the directions taken by the

[1] For an explanation of this process, see the writer's paper, "Exfoliation as a Phase of Rock Weathering," *Journal of Geology*, Vol. XXXIII (1925), pp. 793–806.

cracks are much influenced by various lines of weakness, such as stratification, "blind joints," rift, veins, and schistosity; and therefore the process may yield fragments of many shapes and sizes. Fire spalling affects nearly all rocks that are firm and coherent, especially the hard, brittle igneous rocks, quartzites, flints, and limestones. In friable conglomerate and sandstone its effects are less characteristic, although often quite as extensive.[1]

In order to learn more about the conditions that influence the process of fire spalling, and to determine whether insolation could be

FIG. 2.—Characteristic spalls of quartzite broken off from outcrops on the west side of the Medicine Bow Mountains of Wyoming. The sharp edges and concave surfaces are distinctive.

responsible for any of the result, a series of experiments was carried out by Mr. Robert Loofbourow, under the writer's direction, in the metallurgical laboratory at Stanford University. An electric furnace with automatic control was used in most of the trials. The rocks used in these experiments were sound beach pebbles or quarry blocks of various granites, basalts, andesitic porphyries, hornfels, and graywackes. The pebbles were 2–4 inches in diameter and appeared to be initially free from minute cracks and other flaws. An outline of these experiments follows:

[1] Buckley (*op. cit.*) describes the weakening of certain sandstones by the action of high temperature to such an extent that they could be crushed between the fingers. Presumably this was due to destruction of the cement, which may have been calcareous.

TABLE OF EXPERIMENTS

1. A large pebble of andesite, about 6 pounds in weight, heated quickly to 200° C. and immediately plunged into cold water. This treatment was repeated nine times without developing visible cracks or perceptibly weakening the rock.
2. A quarry block of basalt (4×3×5 inches) was heated rapidly to 200° C. and then dropped into cold water. The treatment was repeated twelve times without visible effect.
3. A similar block of basalt was heated rapidly to 300°C. without visible effect. It was then dropped suddenly into cold water. After this treatment had been twice repeated, several minute cracks were observed.
4. Obsidian, in the form of an ordinary hand specimen, was heated rather rapidly to a temperature of 350° C. and then dropped suddenly into cold water, without visible results. After this treatment had been repeated twice, a large crack was found extending nearly through the specimen. There were also several minute short cracks.
5. A quarry block of basalt was put into the furnace at 300° C. and left there for thirty minutes without results. The temperature was then raised to 325° and maintained for three hours. During that time a few thin flakes broke off from the sides.
6. A similar block of basalt was heated quickly to 375° C. and kept at that temperature for half an hour, with the result that it broke violently into a considerable number of pieces while still in the oven.
7. A river pebble of massive graywacke (3 inches thick) was heated to 350° C. Thereupon several thin slabs split off along almost imperceptible planes of stratification, while still in the oven.
8. A block of basalt was put into the furnace at a temperature of 150° C. without result. The heat was then increased to 400° C. and at that temperature flakes began to break off. With the temperature then constant for about ten minutes, the spalling continued until the block was almost wholly reduced to fragments.
9. A roughly cubical quarry block (3 inches) of basalt was put suddenly into the furnace at 600° C. After about three minutes small scales began to break off and the action continued for ten minutes.
10. A joint block of dense hornfels (3×4×6 inches) was introduced suddenly into the furnace at 600° C. and then allowed to cool slowly overnight. No change in strength or appearance was noted, except that the block broke into two parts along a minute vein of quartz and epidote.
11. An elliptical beach pebble of fine-grained pink granite was heated slowly and raised in the course of two hours to a temperature of 880° C. and then allowed to cool for ten hours. Except for a slight deepening of the color, the only visible change was a single minute crack normal to the surface.

These trials seem to indicate: (*a*) that most, if not all, igneous rocks will withstand repeated sudden heatings and coolings through a range of more than 200° C. without damage; (*b*) that they will generally begin to fail under such treatment between 300° and 375° C.; (*c*) that most of them will, however, endure slow heating and slow cooling through a range of 400°–600° C.; (*d*) that there is great difference in the capacity of various rocks to resist temperature changes; (*e*) that the most susceptible rocks, such as volcanic glass, will tolerate a sudden temperature change of more than 200° C., whereas the most resistant rocks, such as acidic granite and quartzite, will endure slow temperature changes of about 800° C.; and (*f*) that the repetition of the change many times has no visible effect upon the rock unless it approaches the extreme temperature range which the rock is capable of withstanding.

From these results the writer concludes that insolation, or diurnal changes of temperature, are entirely inadequate to cause rock breakage. Even under the most favorable circumstances—as where a black rock surface in a hot desert has been heated to 70° C. (=158° F.) and then cooled by a thunder shower to perhaps 5° C. (=41° F)—the change could not be as rapid as in our experiments No. 1 to No. 4. In such a case the limit of endurance of even the most susceptible rock would not be approached within 135 degrees, and that of a common rock, such as basalt, within 260 degrees C.[1] The data strongly suggest that many repetitions of such expansion and contraction, far below the temperatures at which breakage took place in our experiments, would not serve to bring about fracture. These considerations therefore seem to confirm the field evidence, already presented,[2] that insolation is not an important factor in weathering. On the other hand, they clearly prove the capacity of fire to shatter rocks quickly under conditions that are common.

The field evidence is abundant, but has received little notice. On the broad plateau of the Medicine Bow Mountains, as well as in

[1] Buckley (*op. cit.*) found that all of the building stones tested by him were more or less damaged by subjection to furnace temperatures of 600° to 800° C. Certain granites merely developed a few cracks above 550° C.; some withstood 450° C. without apparent injury; and most of the rocks investigated by him showed but little signs of injury below 400° C.

[2] E. Blackwelder, *op. cit.*

the Sierra Madre and other ranges in southern Wyoming, the writer has found nearly every bowlder and outcrop in the forested zone thus cracked and rounded and the adjacent ground strewn with spalls. The effects of all other weathering processes were insignificant in comparison with those of the repeated conflagrations. Similar conditions were noted along the semi-arid eastern flank of the Sierra Nevada in California. In such localities it is probable that fire spalling demolishes exposed rocks much more rapidly than the more common but less violent processes, such as chemical disintegration. The effect of fire is especially prevalent in those extensive

FIG. 3.—Glacial bowlder of white quartzite surrounded by curved spalls which have been split off by forest fires. Medicine Bow Mountains, Wyoming.

areas where the late Pleistocene glaciers left many outcrops and innumerable bowlders of hard, undecayed rock.

It is noteworthy that no such spalling was observed on the high rocky summits above timber line, and only locally down in the sagebrush zone (Transition life-zone) along the foothills. It was, however, just as prominent in some places where open glades, without trees, appear in the forest. There, it seems probable that the forest was obliterated long ago by severe fires and has not yet crept back over the ground, for the writer knows of no other reason for the lack of trees in situations distinctly favorable to their growth.

The effects of fire spalling are so easily recognized, in comparison with those of other weathering processes, that they should be readily identified in many other places. The curved spalls of sound unde-

cayed rock are very distinctive. It would be interesting to know whether the phenomenon is coextensive with the forest zone of at least the semi-arid regions. In more humid areas fires are less frequent and a more continuous covering of soil insulates the solid rock. In the tropical moist regions the rate of rock decay by chemical action is relatively so much faster that it may overshadow the effects of fire spalling. Where rock outcrops are already well decomposed on the surface, fires would have no opportunity to make spalls, and might do nothing but promote the general crumbling of the rock. Hence the effects of fire on rocks are largely confined to regions in which conditions are favorable.

THE STRATIGRAPHICAL POSITION OF THE KEEWATIN

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ABSTRACT

One of the main points in the classification of the pre-Paleozoic rocks of Canada is the position of the Keewatin series, which is often regarded as comprising the oldest of known rocks. Evidence from Harricana, Porcupine, and other districts suggests that the Keewatin series is either approximately or completely contemporaneous with the Timiskaming series. This position of the Keewatin is also supported by comparison with the Scottish pre-Paleozoic succession.

Canada is the classic land of pre-Paleozoic geology, and since the work of Logan it has been expected to supply the standard pre-Paleozoic classification and succession; yet the Canadian literature on this subject in recent years shows extreme divergence of opinion. Dr. W. H. Collins has remarked that the attempt at a general correlation of the Canadian pre-Paleozoic is premature, and suggests that geologists should for a decade exercise a self-denying ordinance in regard to it. The late Dr. W. G. Miller expressed his agreement with this policy.[1] The Canadian classifications generally adopt a threefold division. The lower division consists of a basement complex of gneisses, schists, sediments, and lavas, which has been intruded by the Laurentian gneiss. The middle division consists of less altered, well-stratified rocks, mainly sedimentary; its general name, the Huronian, according to some authorities (e.g., Miller and Knight) has so largely lost value from varied usage that they recommend its abandonment. The uppermost division, the Keweenawan, consists of sediments and volcanic flows with basic sills and dykes, and intrusions of Killarney granite. In this classification the critical position is that of the Keewatin series. The term Keewatin has been used in three senses: (1) as the name of a series of unfoliated sediments and volcanic greenstones with pillow lavas, younger than the main complex of gneiss and schist; (2) as the name

[1] *Rept. Brit. Assoc., Toronto, 1925*, p. 386.

of the oldest known sedimentary rocks; (3) as a general name for all the pillow lavas and green schists of the region around the Great Lakes.

The first use is the oldest, as the name was given by Professor A. C. Lawson, in his famous "Report on the Geology of the Lake of the Woods Region,"[1] to the volcanic greenstones (including some hornblende schists) of the Lake of the Woods, which are associated with slates, grits, and the Ironstone formation. These rocks have since been found well developed and widely distributed in Ontario, as in the Porcupine gold field and in northwestern Quebec.

The second use of the name extends it to all the sedimentary rocks of the lower pre-Paleozoic division, to distinguish them from the Laurentian or igneous rocks intrusive into the sediments. Thus N. H. Winchell[2] refers to the Keewatins as the oldest rocks in the world, and Professor Grout has recently[3] reasserted that "The Keewatin greenstone remains 'the oldest known rock.'" This interpretation of the name has been widely adopted beyond Canada, as in India,[4] and in Britain where the sedimentary schists found in the Lewisian gneisses of Loch Maree in northwestern Scotland have been identified as Keewatin.[5]

The view that the Loch Maree schists are the Scottish equivalent of the Keewatin has been often accepted in British geology.

The third use of the term, as a petrographic name for various pre-Paleozoic basic rocks and for schists which may be foliated basic igneous rocks, is less important. The dangers inherent in this method of correlation are realized by some Canadian geologists. Thus M. E. Wilson says, "As a consequence of this unscientific method of correlation, the name Keewatin, while presumed to represent a definite formation, in reality is now applied in the Canadian pre-Cambrian subprovinces to any metamorphosed volcanic rock without regard to age."[6]

[1] *Geol. Surv. Canada, Report, 1885*, p. 14CC.

[2] *American Geologist*, Vol. XXII (1898), pp. 262–63.

[3] *Bull. Geol. Soc. Amer.*, Vol. XXXVI (1925), p. 362.

[4] T. H. Holland, *Mem. Geol. Surv. India*, Vol. LI (1926), p. 16.

[5] Miller, *Ontario Bur. Mines, Rep.*, Vol. XX, Part I (1911), pp. 266, 268.

[6] *Geol. Surv. Canada, Memoir No. 103* (1918), p. 67.

At present the general use of the term Keewatin in the United States and Canada is as the name of the oldest rock series of the region.

As one of us visited some typical Keewatin areas in Canada in 1924 under the impression that the Keewatin rocks are the lowest known stratigraphical horizon in Canada, he was surprised to find, especially in the Porcupine district, that both the Keewatin pillow lavas and their associated sediments resemble the Loch Awe series of Scotland rather than the much older schists of Loch Maree. The lithological resemblance of the Loch Awe and Keewatin series throws doubt on the Keewatin rocks being the oldest known formation.

The typical Keewatin rocks are unfoliated sediments and lavas. The latter are often vesicular and spherulitic, with the vesicles and spherules but little compressed. Most of the spherulitic selvages are remarkably perfect. The lavas are no more altered than the Scottish Loch Awe greenstones. Foliation is of course no proof of age; but when large areas of unfoliated and foliated rocks occur together in the same region, clear evidence is required before the foliated rocks are accepted as younger than the unfoliated.

The view that the Keewatin rocks are the oldest in Canada is moreover inconsistent with much recent geological work. Thus at Kirkland Lake the Keewatin lavas are interbedded with slates and graywackes, as recorded by Brock, Bowen, and Wilson.[1] Another striking instance is that of the Harricana district near the western border of Quebec, south of Amos on the Canadian National Railway and northeast from the Porcupine gold field. The sediments there were mapped by J. A. Bancroft in 1912 as Timiskaming. George W. Bain in 1925 showed that these sediments are pre-Keewatin and named them the Okikeska series.[2] They underlie a series of pillow lavas and carbonaceous slates which appear to be correctly identified as Keewatin. If Bain be right in his identification of the Harricana pillow lavas as Keewatin, then his Okikeska series is the earlier and the Keewatin is not the oldest known stratigraphical unit.

The evidence at Harricana, however, goes farther. There are

[1] Cf. H. C. Cooke, *Jour. Geol.*, Vol. XXVIII (1920), p. 307.

[2] *Jour. Geol.*, Vol. XXXIII (1925), p. 728.

two granites—an earlier Algoman and a younger Killarnean—which is the last of the three pre-Paleozoic granites and is Keweenawan in age.[1] Referring to the earlier of the two granites, Bain states:

> This granite was in turn cut by Keewatin dykes, proving that it belonged to the pre-Keewatin rocks of the region. The ancient sediments, therefore, are not only older than the Keewatin, but they were folded, intruded by granite and eroded until representatives of this granite were nearly bared, before the period of Keewatin volcanism set in.

It is possible that this part of the Harricana evidence has been pushed farther than the facts justify. The conclusion that the Okikeska beds are older than the Keewatin is not vitiated if the local lamprophyre dykes be regarded as Haileyburian in age and cut by the later Algoman granite.

The Harricana evidence is the less surprising since a relatively late age for the Keewatin and its complete or approximate contemporaneity with the Timiskaming series has been suggested by facts previously known. Thus, in H. C. Cooke's survey of the Larder Lake area,[2] he determined some of the sediments as Timiskaming in age and as disposed in a syncline, in the center of which occur certain basalts "indistinguishable in appearance from the ordinary Keewatin basalt. Pillow structure is very beautifuly developed along the north boundary of C.E. 33." According to this view there are rocks of the Keewatin type at Larder Lake younger than the Timiskaming; but Cooke later points out that the Timiskaming at Kenogami and Larder Lake lies unconformably above the Keewatin and includes many pebbles from that series.[3]

In the Porcupine district itself there is accumulating evidence that the Keewatin rocks are not older than the Timiskaming series (i.e., Sudbury series). In a letter, Mr. J. B. Tyrrell remarks that the rocks of a large area lying east of Porcupine have been identified as Timiskaming and were consequently held to be younger than the Keewatins. He informs us that the contrary is the case, for the contact is clear and the base of the lowest flow can be distinctly seen resting on the quartzitic graywacke. The correlation which is

[1] Collins, *Geol. Surv. Canada, Mem. No. 143* (1925), p. 93.

[2] *Geol. Surv. Canada, Mem. No. 131* (1922), pp. 19, 27.

[3] *Ibid.*, p. 36.

generally accepted was made before the tops and bottoms of the lava flows had been distinguished. Further information is available from his observations in the Dome mine and they lead him to believe that the marking of the corrugated slate is really ripple marking. The lavas can be seen to have flowed over the ripples and taken their impression. Hence, according to Mr. J. B. Tyrrell, as regards Porcupine, the Keewatin lavas overlie sediments which have been identified as Timiskaming. At Larder Lake[1] it has been shown that the sedimentary rocks which were supposed to be interbedded with the Keewatins are part of the Timiskaming series. Again, in the recent memoir by Collins, Quirke, and Thomson on the Michipicotin Iron Ranges,[2] the Dore series of Logan is redescribed and interpreted by Collins and Quirke (p. 41) either as inter-Keewatin sediments, or as pre-Keewatin by Thomson (p. 145). And the Dore series has been sometimes identified, as by Coleman and Parks,[3] as a local representative of the Sudbury-Timiskaming series. Hence here also the typical Keewatin formation is underlain by an unmetamorphosed sedimentary series.

We need not enter into the general correlation of the Canadian pre-Paleozoic series; but the relation of the Keewatin series to the Grenville series must be considered, since, according to Miller and Knight, the two series were contemporary. Thus in their notes of map 22—Sudbury-Cobalt-Porcupine—Miller and Knight group the Keewatin and Grenville as a basal system, the Loganian. They regard the Keewatin as submarine lava flows and hold that a part of the Grenvilles is contemporaneous with them.[4] We can find no specific case of contact between the Grenville and Keewatin rocks, and none occurs in the Porcupine area. The nearest outcrop of Grenville occurs at Lake Kipawa, about 110 miles to the southeast of Porcupine. The Grenville series reappears farther north, according to H. C. Cooke,[5] as the Nemenjish Series of Kaopatina, 100 miles northwest of Lake St. John. Dr. Cooke regards this series as con-

[1] Cooke, *Jour. Geol.*, Vol. XXVIII (1920), p. 332.

[2] *Geol. Surv. Canada, Mem. No. 147* (1926), pp. 24, 41, 145, etc.

[3] *Geology* (1922), p. 173; also Coleman, *Congr. Geol. Intern.*, Vol. XII (1913), p. 396.

[4] *Ontario Bur. Mines Rep.*, Vol. XXII, Part II (1913), p. 85.

[5] *Jour. Geol.*, Vol. XXVII (1919), p. 184.

formably overlying the basic lavas of that district, which have been correlated with the Keewatin; but as he doubts that correlation, he has adopted for those lavas Wilson's name of the Abitibi series.[1] Their identity with the Keewatins of the Porcupine district appears as probable as their difference in horizon from the Lower green schists in the Lake Superior basin that have been called Keewatin.[2]

Cooke, however, admits that the evidence for the superposition of his Nemenjish garnetiferous gneiss on the basic pillow lavas rests on one doubtful exposure,[3] and his map[4] suggests from the general distribution of the Nemenjish series that it is as likely to be pre-Abitibi.

The fact that the Nemenjish rocks do not overlie the upper lavas is recognized by Cooke[5] as a difficulty.

The igneous rocks associated with the Grenville series are quite different from those associated with the Keewatin, and that fact supports the difference in age of the two horizons. The Grenville rocks include coarse sillimanite-gneisses which indicate a regional metamorphism from which the often undeformed Keewatin lavas have escaped. The evidence for the Grenville-Keewatin correlation is admittedly weak. Dr. T. T. Quirke is of the opinion that "the volcanic, stratigraphical, and structural evidences, as far as they are known, indicate that the Grenville series of southeastern Ontario should be correlated with the Huronian series of the north shore of Lake Huron."[6] Dr. Quirke, on this view, though representing the Keewatins as older than the Grenvilles, merely makes them pre-Huronian.

In face of the striking lithological differences between the Grenvilles and Keewatins, the arguments for their correlation carry no conviction in opposition to the general rule that highly metamorphic rocks in extensive areas are older than the non-foliated series of the same district.

If, therefore, the Harricana and Porcupine pillow lavas are correctly identified with the typical Keewatin of Rainy Lake, and this conclusion appears to be universally accepted, the Keewatin beds are not the oldest Canadian rocks.

[1] *Ibid.*, pp. 69, 70, 274.
[2] *Ibid.*, p. 274.
[3] *Ibid.*, pp. 270–71.
[4] *Ibid.*, p. 185.
[5] *Ibid.*, p. 272.
[6] *Jour. Geol.*, Vol. XXXII (1924), p. 335.

The Rainy Lake succession is historically the standard for the Keewatin series; but the determination of its relations is there especially difficult, for the belt of sediments and volcanic rocks is nipped in between two masses of intrusive granite, so that the beds are disturbed and altered. Farther north in the western region the rocks are still much altered; but though the pillow lavas of Silver Island on the Lake of the Woods are more altered than at Porcupine, there is no essential difference between them. Mr. Bruce told one of us that he regarded the round bodies in the selvages of the lava pillows at Silver Island (Lake of the Woods) as altered crystals and not as spherulites; this view illustrates the more altered condition of the greenstones there as compared with the Porcupine district.

To the south of the Rainy Lake Keewatins is a belt of gneiss and coarse schist which underlies the volcanic series and must be, as Professor Lawson has so strongly contended, pre-Keewatin. These gneisses he named the Coutchiching. That term has been widely rejected because no doubt too much was originally included in it. But after the extraneous material has been excluded, there probably is a remnant of pre-Keewatin gneiss. The belt of gneiss and coarse schist to the south of the Keewatin rocks includes two chief types: One type, Lawson's Coutchiching, is strikingly like the upper or flaggy type of the Scottish Moine gneiss, in both field characters and miscroscopic structure. The other type, the "banded gneiss" of Ottawa, South Ontario, North Bay, and south of Rainy Lake, resembles the older nonflaggy division of the Moine gneiss as developed in the Scottish Central Highlands. The relations of the banded series to the Keewatin division is uncertain, and the contact appears to be poorly exposed. But we know of nothing to prove that this banded gneiss is younger than the unfoliated rocks to the north of it. The general distribution is consistent with the view that the Keewatin series is the younger and was deposited on the banded gneisses. This conclusion would be untenable if the southern banded gneiss could be found anywhere intrusive into the Keewatin and Timiskaming series; but the gneissose granites intrusive into those series are different in age and character from the banded gneiss which forms the axis of the Great Lakes region and passes south of the Keewatin greenstones.

The Scottish pre-Paleozoic rocks show so many striking resem-

blances to those of Canada that it is tempting to consider whether the same types of rocks do not occur in the same sequence. Both countries include similar main types: (1) the unaltered red sandstone series; (2) a series of indurated and unfoliated quartzites and slates, with some volcanic rocks—the upper beds may be gently and the lower steeply tilted; (3) a stratified series of mica-schists and gneiss, crystalline limestones, and schistose quartzites; (4) a thick gneiss clearly due to the alteration of sandstone with interbedded clays; and (5) gneisses of foliated igneous rocks.

If the series in Canada and Scotland correspond in age, the correlation may be as in Table I.

TABLE I

Canada		Scotland
Keweenawan		Torridonian
Huronian	Cobalt series	Slates, epidiorites, Highland Border series
	Bruce series (largely quartzite, etc.)	Schichallion quartzite and bowlder bed
Pre-Huronian	Keewatin lavas and Timiskaming (Okikeskan, Sudbury Mattagami, etc.) sediments	Loch Awe and Blair Atholl series of Upper Dalradian
	Grenville	Lower Dalradian
Loganian	Coutchiching	Moine gneiss
	Laurentian (gneisses and schists)	Lewisian gneiss (and Loch Maree schists)

It may be remarked that any such correlation in the absence of fossils is uncertain. The pre-Paleozoic rocks can only be correlated on petrographic and stratigraphic evidence. The lithological resemblance of the Canadian and Scottish series, below the Cobalt, is quite remarkable. In both countries there are three series of intrusive granites or granitic gneisses. The oldest are the Laurentian and Lewisian.[1] In Canada the Coutchiching and Grenvilles are invaded by the Algoman granites which correspond in position to the Scottish granites that are intrusive into the Moine and Lower

[1] The view that the Laurentian should include the middle series of granites and not the oldest (as suggested by H. C. Cooke, *Jour. Geol.*, Vol. XXVIII [1920], p. 331) abandons its traditional meaning.

Dalradians (such as the older granites in the Moine near Blair Atholl and in the Ben Lomond series near Pitlochry); and the third Canadian granite, the Killarnean, may be compared to the gneissose-granite intrusive into the Schichallion quartzite at Meall Gruaim, Glen Tilt. The Scottish succession is as debated as the Canadian, and according to one view the Moine is altered Torridonian. Scottish opinion appears unanimous that the Lewisian gneiss is the oldest Scottish division, and that the Dalradian rocks are earlier than the rocks correlated in the foregoing table with the Cobalt.

The correlation suggested in the table is consistent with Professor Lawson's view that the Coutchichings are part of a widespread lower gneiss and correspond with the Ottawa gneiss. The analogy of Canada with Scotland supports that view and also that this gneiss and schist series is older than the unfoliated sediments and lavas which occur to the north of it. The Keewatin, Timiskaming, and associated series appear to have been deposited on the northern side of an older area which is composed of holocrystalline foliated rocks that extend from Rainy Lake eastward to the north of Lake Superior, past North Bay and Lake Huron to southeast Ontario and the St. Lawrence Valley.

We therefore conclude, after due consideration of Professor Grout's interpretation of the Bear Passage section at Rainy Lake, that the broad area of gneiss and schist to the south of the Keewatins at Rainy Lake, and the band of gneiss and schist that passes North Bay to southeast Ontario, formed the foundation upon which the later rocks were laid down; that the original Keewatins of Rainy Lake and the Lake of the Woods have been correctly correlated with the less altered Keewatin pillow-lava series of Porcupine and Harricana; and that the green schists of Michigan and Minnesota, which have been correlated with the pillow lavas, are pre-Keewatin.[1] Further, that the Keewatin pillow lavas and associated rocks correspond to the Loch Awe series which is high in the Scottish pre-Paleozoic succession.

[1] The conclusion that the Keewatins include beds of different ages was adopted by McInnes in 1899 (*Ann. Rep. Geol. Surv. Canada*, N.S., Vol. X, p. 19).

FORMATION OF CLAY BALLS

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ABSTRACT

Spherical masses of clay, "clay balls," are produced under certain conditions by the action of water, and, as such, have been found fossilized. In some cases, accretion seems to be the chief factor in their formation; in others, a wearing away of the projecting parts. In arroyo development the balls are formed by the latter method.

Irregularly rounded balls of clay have been observed, not uncommonly, along the beach of Lake Michigan north of Evanston, especially in the vicinity of Highwood and Waukegan. Along these sections near the water's edge are high clay bluffs, oversteepened by undercutting, which become the scene of considerable slumping during a protracted period of wet weather. At such times large masses of a very stiff, tenacious clay slide down within reach of even the smaller waves. Loose pieces, or parts broken off the main mass, then are moved back and forth, over either a clay or a sandy base, gradually getting smaller and smaller in the process until entirely wasted away. As they roll over and over, the projecting parts, naturally, are worn away fastest and the lump assumes a spherical or, in many cases, because of the back-and-forth movement mainly, a slight elongated form. They may vary in size as observed from that of a small marble up to 10 or 12 inches in diameter.[1]

Mr. William B. Phillips[2] reports that in the concentration of Alabama iron ores he has experienced considerable difficulty because of the tendency of the clay particles to ball and then carry away some of the iron. These balls never were larger than small nuts, probably because of the short distance traveled. Their forma-

[1] During the summer of 1920 Professor W. W. Mackie, of the University of California, found some clay balls, "tending to be spherical in shape," on the beach of Lake Tulare. "These balls varied in size from small ones an inch in diameter to those of five or six inches. They were quite hard and did not appear to soften when they lay in the water, rolling about under the action of the waves" (personal communication).

[2] "Iron Making in Alabama," *Geol. Surv. of Ala.* (1912), pp. 78, 79.

tion, however, was unquestionably due to the addition of material from the outside, and conceivably they might have become much larger had the distance traveled under similar conditions been much greater.

In the Rio Chaco, New Mexico, Mr. James H. Gardner[1] found clay balls, averaging about $1\frac{1}{4}$ inches in diameter, which he believes

FIG. 1.—Clay balls and other material carried out from an arroyo during a local flood. A large number were partly or wholly buried in the débris. The north escarpment of the mesa is in the background.

were truly concretionary. The author describes their origin as follows:

> The origin of the concretions is not difficult to explain. In the superconcentrated or overloaded water carrying fine clay particles along a smooth bottom, an adhesion of those particles naturally results. They are pressed together as are finely disseminated particles of butter in the everyday illustration of churning. They may unite with or without a nucleus. A soft nodule will form, grow, and become rounded by being rotated along the different axes as boys roll snowballs. It will be propelled by the current, gathering as it goes [p. 455].

[1] "The Physical Origin of Certain Concretions," *Journal of Geology*, Vol. XVI (1908), pp. 452–58.

Much interest has been attached to the clay balls found in the drift in Illinois and Wisconsin.[1] Those in northern Illinois are familiar to geologists of the region, but no study of them, thus far, has appeared in print. The late Mr. A. J. Ellis, of the United States Geological Survey, kindly sent the author an abstract of an unpublished paper written as a result of considerable study on the clay balls in the Illinois and Des Plaines valleys, and also as a result of

FIG. 2.—Material spread out at the mouth of an arroyo. Some of the balls are seemingly perfect spheres; others are merely irregularly shaped lumps, as may be seen in the middle foreground.

considerable experimentation in the laboratory at Northwestern University. His description and conclusions are as follows:

The clay balls collected at Spring Valley near LaSalle and examined in the laboratory were nearly all spherical, ranging in size from one-half inch to twenty inches in diameter, and the large ones were much more round and smooth than the small ones. They were covered on the outside with small pebbles sticking into the clay, as a rule not protruding, but pressed well in so that the surfaces were fairly smooth. On breaking open the balls I found a variety of structures. (1) Some of them were quite homogeneous throughout with only small pebbles

[1] The author is indebted to Professor John R. Ball, of Northwestern University, for the location of the balls in the drift near Milwaukee, Wis.

scattered through them. Balls of this kind were generally small; none were over two inches in diameter. The pebbles sticking into them on the outside were also small and were not numerous. (2) Other balls were made up of a nucleus resembling in every respect the balls just described, covered with a shell of clay and pebbles that varied in thickness up to one-half inch. Pebbles were much more numerous in the shell than in the nucleus, but were usually quite well distributed through the former, being as plentiful in the inner portions as at the surface. The shell was not so firmly fixed to the nucleus that it could not be readily peeled off. (3) The third type resembled the last described, but differed in having a nucleus made up of distinct lumps of clay. In one specimen the nucleus was made up of two lumps which appeared to have been stuck together and then covered with the shell.

As a sort of general conclusion, I arrived at the following simple explanation. Water, either in ordinary streams, braided streams, or sheet floods, issuing from the glacier front, passed over deposits of clay and till under conditions which probably favored vigorous cutting and shifting of stream ways. Some masses of till and clay torn from the ground or falling from undercut banks were firm enough and plastic enough to be carried or rolled along by the water and assumed a rounded or spherical form, not so much by corrasion as by moulding—by the combined pressure of their own weight and the rolling motion. They probably grew by accretion when they rolled over clay floors, and on passing over gravel picked up the pebbles that stuck into them. Later additions of clay and gravel produced thick shells like those observed in some of the balls at LaSalle. When two or more balls became squeezed together, they were carried along as one, thus producing the balls with compound nuclei. It seemed to me that this explanation was adequate for all the balls I observed in the LaSalle area, and was consistent with the condition of affairs along the Lake Michigan shores, as well as with those which by analogy probably existed along the glacial lake shore near Joliet. As you will note, I discarded the idea that frozen lumps of till were rounded into spherical forms by processes comparable to those which produce ordinary glacial boulders, or by any other process.

It will be noted from the studies cited that there are two views as to the formation of clay balls: the one is on the principle of accretion, the other is on the principle of corrasion. In the one case, the ball gets larger; in the other, smaller. It seems entirely possible that, under proper conditions for each case, both types of balls may be developed. The present writer, however, is inclined to doubt the formation of the larger balls by accretion. In the illustration of the snowball used by Mr. Gardner, the tendency is to become not spherical but angular. Not enough broken drift balls have been studied to verify or deny Mr. Ellis' conclusions.

The author has had occasion to study erosion in the Mesa Verde region of southwestern Colorado, and has observed, and actually followed on horse, rolling masses in times of high water. This was along the Mancos and Montezuma valleys bordering the steep north escarpment of the Mesa Verde. The region is semidesert, growing little aside from the common sagebrush. The rainfall along the thousand-foot escarpment is much heavier than in the valley beyond

FIG. 3.—Clay balls from an area of about 2 sq.yd. The size may be noted in comparison to the hammer handle. Irregularly shaped masses may be noted in the foreground. The cracking is due to the penetration of moisture. The pebbly appearance of some is due to the unweathered shale particles which are picked up during the rolling process and are found only on or near the surface.

the compound alluvial fans, and the flood-waters from the higher parts not uncommonly reach a dusty valley where no rain has fallen for some time.

The escarpment, except the capping, is made up of the easily eroded Mancos shale, which weathers into a very stiff adobe. As a result, the water coming from the steep shale slope, in the form of sheet wash, is very heavily laden with clay particles and débris of various sorts, so much so that the liquid mass as it pushes, now here, now there, has little resemblance to running water. As the mass

spreads out over areas less steep, it deposits some of its material and builds up an alluvial fan. Owing to the better moisture conditions, the fan becomes a favorite area for some of the wild annuals, especially the sunflower, and the dense stand of these plants—barriers to the moving viscous mass—helps to steepen the deposit still more. In this way enormous deposits of very finely comminuted clay particles are built up all along the north escarpment.

FIG. 4.—One of the larger and more open arroyos after a recession of flood waters. A block too large to be rolled may be seen on the left and numerous small ones within the stream. On the right is a huge block outlined by ground cracks ready to topple over with the next flood.

In the general stripping process of the region, these oversteepened deposits are moved again to lower areas, and here the transfer generally is started by the cutting of arroyos. Their mouths in these cases are commonly near the same level as the immediate surroundings, and the material carried is spread out again over the adjoining area more or less fan shaped. The adobe into which these arroyos are cut, although very sticky when wet, becomes unusually hard when thoroughly dried out, developing enormous ground cracks. As

a result, the depth of the arroyos may be as much as 20 or 30 feet, with only a few feet across the top. In the main, however, their depth is about three times their width at the top. Since the erosion seems to be more active when the adobe is less dry at or near the bottom, the walls, for the most part, are vertical and even overhanging, and the width at the bottom in places may be twice that at the top.

FIG. 5.—Balls of various sizes. Some broken to show homogeneous interior structure. Occasionally particles of shale were found in the interior, but such also may be found in the arroyo walls. When these balls come to rest, the interior is perfectly dry and the surface a soft, smeary mass.

During heavy downpours, the only time there is any running water, the arroyo is soon filled with a raging torrent. As the water is already heavily loaded, erosion is relatively slight, but there is some undercutting, and large blocks, weakened by the huge cracks, break off and are rolled down the stream. Most of these blocks are bone dry when they fall into the water, and are remarkably resistant to the penetration of moisture. As they are rolled over, the projecting corners are the first to be softened and worn away, and the more or less protected hollows may even be filled somewhat. If the arroyo opens on to a broad flat instead of into another arroyo, or stream,

these rounded lumps of clay may be rolled along considerable distances and scattered about rather indiscriminately, or, in some cases, with a sudden drop of the waters they are left stranded within the arroyo (Figs. 1–4).

Many of these rounded pieces are nearly perfect spheres. They vary from about 1 inch to 12 or 14 inches in diameter, but the size is limited only by the power of the water to turn over the mass, or by the narrowest part of the channel through which they have come. The balls as they roll along appear as soft, sticky masses, to which particles of shale and other material cling; but if they are broken apart shortly after they come to rest, the major part of the interior of the larger ones may be perfectly dry with a moisture penetration of less than an inch (Fig. 5). In a few hours, however, the moisture reaches the center, the whole mass mellows, and with the return of the sun the balls dry and fall apart. Of the scores which the author has broken apart, not a single one showed a concretionary structure. They are never preserved unless completely covered at the time of the wash.

These clay balls may have considerable importance in explaining many rounded bodies now known as "concretions," perhaps even some *Septaria*, and also in explaining the origin of clay balls found in till in the vicinity of LaSalle and Joliet, Illinois, and Milwaukee, Wisconsin. It would be difficult to imagine conditions such as those observed in Colorado and already cited to have obtained during the glacial period, for we do not think of the glacial period as one of great aridity. On the other hand, an origin similar to that of the clay balls or rolls formed where the lake-waves are actively cutting would seem a much more reasonable explanation. The clay balls found in the till are round because rolled forward by water. They would be subject to counter-currents, and their movement would be not only in one but in many directions. The chief requirement that would seem necessary would be a slumping of stiff, tenacious clay into moving water.

CONCERNING THE DIFFERENTIATION OF A LAMPROPHYRIC MAGMA AT CORBALEY CANYON, WASHINGTON

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ABSTRACT

Evidence is presented to prove that the dike rocks of Corbaley Canyon represent a series of intrusions injected at intervals during the differentiation of an original lamprophyric magma. A very complete series of differentiates, with a quartz-hornblende kersantite and a spherulitic granophyre as the poles, has been found. That differentiation did not proceed by the splitting of a magma of intermediate or of granitic composition into acidic and basic poles to form "complementary dikes" is proved by the fact that the basic dikes were intruded earlier than dikes of intermediate and granitic composition.

It is thought possible that the original lamprophyric magma from which the differentiates were formed may represent one of the lamprophyric offshoots of the Mount Stuart Batholith which lies about 20 miles to the southwest.

INTRODUCTION

Corbaley Creek, locally called Pine Creek, is a small stream entering the Columbia River from the northeast in Douglas County, Washington. Its headwaters lie upon the basaltic plateau which forms the greater part of central and eastern Washington. About 7 miles above its mouth it cuts through the overlying basalt and deep into the gneissic basement upon which the lava floods were poured out. The entire drainage area of the creek is included in the Chelan Quadrangle, Washington, of the *Topographic Atlas of the United States*.

As Corbaley Creek nears the Columbia it becomes intrenched in a steep-sided canyon (Fig. 1), the walls of which widen upward at an increasingly faster rate, forming a V with flaring sides. This feature testifies to more than one stage of canyon-cutting, each stage of different intensity, and identifies the region as a part of the district in Central Washington which has become famous in Pacific Coast physiography through the work of Bailey Willis.[1]

[1] Bailey Willis, "Physiography and Deformation of the Wenatchee-Chelan District, Cascade Range," *U.S. Geol. Survey, Professional Paper 19*, Part 2, 1903.

The walls of Corbaley Canyon are sufficiently steep to prevent the accumulation of soil or débris of any kind except in small places that are more or less protected, but at the same time they are not so steep as to render them inaccessible to a man on foot. These walls, therefore, furnish excellent workable exposures, upon which the most minute details of the geology can be easily observed.

FIG. 1.—Corbaley Canyon from Waterville plateau. Dikes cutting the softer gneiss can be seen outcropping as ridges on the right side of the canyon. The large fog-filled valley is that of the Columbia.

GEOLOGY OF LOWER CORBALEY CANYON

RIBBON GNEISS

The lower canyon is cut in granitic gneiss of unknown age. In most localities within the canyon the gneiss is intruded by innumerable stringers and veinlets of alaskitic and pegmatitic material. These injections generally follow the planes of gneissic banding, producing a ruled or ribboned effect in the rock. Many geographic locations have received their names on account of this peculiarity as, for instance, Ribbon Rock, Ribbon Cliff, and Ribbon Mesa. Following this system of nomenclature the writer has called this series of metamorphosed igneous rocks the Ribbon gneiss.

Gneisses of similar characteristics can be seen all along the Columbia River northward from Wenatchee until they merge into the metamorphic basement of the Okanogan Highlands. The Ribbon gneiss occurring in Corbaley Canyon shows a general petrographic resemblance to the Orient gneiss which has been described by C. E. Weaver as occurring in Ferry and Stevens counties, a part of the Okanogan Highland district.[1] The Ribbon gneiss contains somewhat more sodic plagioclases than the Orient gneiss, however. The Orient gneiss is the oldest formation that Weaver records from Stevens County and he regards it as possibly of pre-Cambrian age.

CORBALEY CANYON DIKE SERIES

The graceful curve of the upward sloping walls of Corbaley Canyon is everywhere broken by innumerable jagged spires and minarets caused by the outcrop of a multitude of acidic and basic dikes which cut up through the older gneiss. These, being in general more resistant to erosion than the softer gneiss, betray themselves topographically as long walls with sharp irregular tops. Dikes with similar characteristics cut the older metamorphics at intervals all the way along the Columbia River between Wenatchee and Chelan, but they are nowhere so numerous as in lower Corbaley Canyon and in the Entiat River valley, which lies immediately across the Columbia to the west. In some parts of Corbaley Canyon the dikes make up over 40 per cent of the rocks exposed. From the Canyon, both northward and southward, they decrease rapidly in amount until a few miles from the canyon intrusions breaking the contours of the gneiss are comparatively rare.

The dikes in Corbaley Canyon generally show a rude parallelism in a northwest-southeast direction. Local departures in strike from this direction are numerous, however, and the truncation of one dike by another is a very common occurrence, thus giving conclusive evidence concerning the relative age relations of different intrusions. The dikes vary considerably in width. The majority form intrusions which are between 10 and 35 feet in thickness, but there are many smaller dikes only one foot or less in width, while a few single dikes attain a width of as much as 50 feet. Composite dikes are

[1] Charles E. Weaver, "The Mineral Resources of Stevens County," *Washington Geological Survey Bulletin 20*, 1920, pp. 85–87.

common and in many cases occupy much larger fissures. One composite dike, composed of four chemically different magmas, fills a fissure over 100 feet in width. Multiple dikes are rare. In the field some of the more basic rocks appear to outcrop in multiple dikes, but when specimens from these are studied in thin section, marked differences in composition are nearly always revealed.

VARIATIONS IN COMPOSITION IN DIKE SERIES

In composition the dikes vary from basic varieties to very acidic types. This change is reflected in the color of the rocks, which ranges from almost black in the more basic varieties through dark greenish-gray into light gray and finally through dirty white into yellow in the acidic types. In texture all of the dike rocks are of dense habit; none of the specimens examined was sufficiently granitoid so that the mineral composition could be determined with the naked eye. In thin section, however, it can be seen that the rocks are entirely holocrystalline with no traces of glass except locally along chilled contacts. Both porphyritic and non-porphyritic types are common in the canyon. The most common phenocrysts are feldspars. Quartz is less common and hornblende is rare.

The basic rocks in Corbaley Canyon belong to that group of rocks known as lamprophyres. The petrographic analysis of a 9-foot quartz-hornblende kersantite dike outcropping 500 feet down the highway from Camp Beaver Den, in Corbaley Canyon, shows it to be an even-grained rock in which the constituent minerals have a distinct idiomorphic tendency. Plagioclase, zonal from andesine to oligoclase, and with corroded centers containing numerous inclusions, makes up the major part of the rock. Orthoclase is common. A tendency toward perthitic intergrowth is noted in many crystals, and a few have borders which are micrographically intergrown with quartz, forming micropegmatite. Quartz is also present as a minor constituent, but is exceedingly rare. It forms an interspace filler between feldspars in a few places. Corroded mafics, principally biotite and hornblende, together with the various products arising from their decomposition, make up a large part of the rock. The biotite is somewhat embayed but often exhibits sharply idiomorphic outlines. It usually exhibits yellow to brown pleochroism. Some individuals of biotite vary in pleochroism even in a single crystal.

One part will show absorption from yellow to brown, while an adjoining part in the same crystal varies from yellow to bright green. Hornblende is represented by badly decomposed crystals which are largely converted into chlorite. A small quantity of uralite is also present in the section. Two distinct types of chlorite were noted. One type is of a clear bluish-green color in ordinary light and almost isotropic. The other is more yellowish green, is often clouded, and shows the characteristic anomalous blue under crossed nicols. Magnetite is present in granular aggregates, formed mainly as a by-product in the chloritization of the amphiboles. Apatite is present in long thin crystals. A few altered grains of sphene were also observed. Epidote is developed at the expense of plagioclase feldspar in a few places. A peculiar feature of the rock is that it contains patches of mixed chlorite and carbonate. These aggregates occur both in sizeable patches and as minute grains filling the spaces between the other minerals.

The most acid dikes in the canyon consist of porphyritic rocks containing phenocrysts of quartz set in a fine-grained groundmass composed almost entirely of intergrown quartz and orthoclase, the intergrowths generally occurring in the form of spherulites. Microscopical examination of a spherulitic granophyre of this type which cuts the kersantite described above shows it to be a porphyritic rock consisting of phenocrysts of quartz set in a medium-grained semi-mosaic of graphically intergrown quartz and feldspar. The intergrowths consist both of spherulites and irregular spongelike types. The spherulites radiate outward from a central point; none of them have feldspar crystals as nuclei, as is commonly the case in the other dikes. A few orthoclase crystals occur as phenocrysts. They are rather badly corroded and embayed and are extensively altered, kaolin, sericite, and carbonates being among their decomposition products. The chlorite is a clear bluish green in ordinary light and is almost isotropic. Fragments of decomposed feldspars are also included in the micropegmatite.

DIFFERENTIATION

If the seventy-two specimens of dike rocks collected from an area of a little less than four square miles in the central portion of the

canyon are arranged in order from the most basic to the most acidic they are found to represent an extremely complete transitional sequence between the quartz-hornblende kersantite on the one hand and the spherulitic granophyre on the other. With the decrease in basicity the amounts of micropegmatite in the rocks gradually increase. At first the intergrowths take the shape of the feldspar crystal with which they are intergrown. In the more basic rocks, idiomorphic plagioclases which are zonal from basic andesine to oligoclase will be intergrown in the outer more sodic portion with quartz. In these quartz-plagioclase intergrowths the albite twinning of the feldspar can be seen in both the intergrown and the pure parts of the crystal. This twinning does not affect the intergrown quartz. Adjoining quartz individuals on either side of a twinning line are shown to be in straight optical continuity despite the change in vibration directions in the feldspar caused by twinning. With the decrease in basicity there is also an increase in the relative amount of orthoclase as compared to plagioclase. Orthoclase crystals are almost always intergrown with quartz to some extent. The intergrowths are never idiomorphic, as was the case with the quartz-plagioclase intergrowths, but either are irregular or are crystallized as beautifully symmetrical spherulites. The spherulites are of many different types. Some start with a central orthoclase crystal as a nucleus. These show relatively more orthoclase close to the nucleus and gradually increasing amounts of quartz from the center outward. The feldspar in the intergrowth is always in optical continuity with the feldspar in the nucleus. In some intergrowths these nuclei are shaped like an hour-glass instead of having the usual crystal outline of an orthoclase crystal. Many of the spherulites start from a point and radiate outward in all directions. There is a constant decrease in amount, but no change in kind, of the mafic minerals from the basic rocks to the acidic. Remnants of decomposed hornblende and biotite, together with chloritic and limonitic aggregates, are found included in the micropegmatite in even the most acidic rocks. A peculiar chlorite of a bluish-green color in ordinary light and almost isotropic was found in all but four of the seventy-two sections of dike rocks examined from this portion of the canyon.

In order to show these changes in mineral content without includ-

ing lengthy petrographic descriptions, the writer has assembled the essential facts derived from the study of fifteen of the seventy-two

ROCK COMPOSITION			SPECIMEN NUMBER														
			I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	XIII	XIV	XV
QUARTZ		Total percentage of rock	-1%	2%	4%	4%		3%	3%	1%	1%	1%	5%	40%	11%	16%	4%
	Occurrence	Groundmass	X	X	X	X		X	X	X		X	X	X	X	X	
		Phenocrysts									X		X		X	X	X
	Total percentage of rock		-1%	4%	3%	-1%	21%	62%	66%	65%	85%	84%	77%	46%	80%	78%	91%
MICROPEGMATITE	Types	Spherulites start from ortho. cryst. point								X	X	X	X	X	X	X	X
		Spherulites start from ortho. cryst.					X		X	X	X	X	X	X	X		X
		Non-spherulitic	X	X	X	X	X	X	X	X	X	X		X	X		
	Types	Spherulitic									X	X	X				
		Non-spherulitic	X		X			X	X		X						
ORTHOCLASE		Total percentage of rock	10%	15%	15%	55%	35%		8%	9%		12%	13%	10%	4%	4%	1%
	Occurrence	Groundmass	X	X	X	X	X		X	X			X	X			
		Phenocrysts				X	X			X		X		X	X	X	X
ANDESINE		Total percentage of rock	30%	45%	45%	1%	3%		10%	12%	2%				3%		
	Occurrence	Groundmass	X	X	X	X	X		X	X	X				X		
		Phenocrysts	X	X	X				X	X							
HORNBLENDE		Total percentage of rock	15%	12%	3%	31%	2%	6%	8%	2%	1%	1%	1%		2%	1%	-1%
	Types	Fresh	X	X		X			X	X					X	X	X
		Corroded	X	X	X	X	X	X			X	X	X		X		
BIOTITE		Total percentage of rock	7%	5%			8%		3%	6%	4%	-1%					
	Types	Pleochroic in brown	X	X					X	X	X	X					
		" in brown & green	X				X			X							
GRANULITE		Total percentage of rock	14%	15%	14%	3%	3%	14%	2%	4%	2%	1%	1%	2%	-1%	1%	-1%
	Types	Clear, blue-green, isotropic.	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
		Yellow-green, cloudy, Berlin blue under crossed nicols	X	X	X			X	X		X	X	X		X		
MICROPERTHITE		% of rock	-1%	-1%	5%	-1%	5%			-1%				2%			
OLIGOCLASE		% of rock				4%	1%										
CARBONATE		% of rock	2%					11%	3%	1%							
SPHENE		% of rock	-1%		7%	1%	1%	-1%	-1%	-1%		1%			1%		

FIG. 2.—Differentiation chart

sections which are about equally spaced in the transitional series into a chart which is presented as Figure 2. For this chart an estimation

of the percentage mineral composition of the rock has been made by the process of comparing areas occupied by the minerals in the thin section with the aid of a grid ocular. Many counts were made for each section and the results averaged. It is believed that this method when used with care will give a very close approximation of the true mineral composition. In the chart the fifteen specimens are listed by number, beginning with the most basic, No. I, on the left, and ending with the most acidic, No. XV, on the right. The constituent minerals in the rocks are listed from top to bottom on the chart. Under each mineral special characteristics of the mineral which tend to show a common derivation from a parent magma are listed. If the rock under consideration contains the mineral, and the mineral exhibits one of these properties, it is denoted by an X in the column opposite the mineral characteristic. In some cases where a mineral occurred in very small amounts, considerable difficulty was encountered in telling whether a mineral had certain characteristics or not. In these cases all of the mineral characteristic columns are left vacant. In this chart the quartz-hornblende kersantite already described is specimen No. I. The spherulitic granophyre is specimen No. XV.

The most striking fact that is brought out by a study of the dike rocks in Corbelay Canyon, and a fact that is reflected in the data in the chart in Figure 2, is that *different dikes do not vary in the kind of minerals that they contain, but in the relative abundance of certain constituent minerals.* This fact argues strongly for the hypothesis that the dike rocks in Corbaley Canyon are differentiates from a common parent magma.

The relative age relations of different dikes give added strength to this conclusion. Because of the especially excellent exposures in Corbaley Canyon, definite evidence concerning the relative age of different dikes in the series was easily procured. It was found that in every case individual dikes cut across those that are more basic than themselves and are in turn truncated by the more acidic types. On account of the excellent exposures in the canyon, cross-cutting relations could be observed repeatedly, and in every case without a single exception the rock truncated was more basic than the dike which cut it. Figure 3 is a sketch showing the age relations of three dikes

of different composition at one point in the canyon. Of the dike specimens listed in the chart in Figure 2 the relative ages are known for all but three, and in all cases the older rocks are the more basic.

VISCOSITY CHANGES IN THE MAGMA

Certain features observed regarding the injection and contact effects of the dike rocks in Corbaley Canyon are of interest as furnishing some data regarding the physical characteristics of the magmas which formed the intrusions in this district. The type of

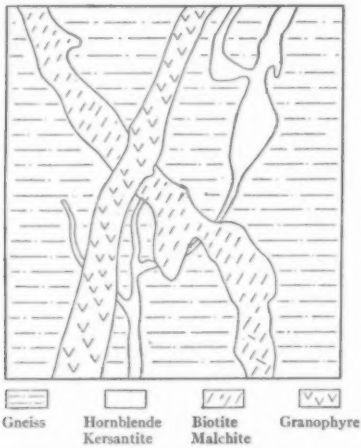

FIG. 3.—Sketch showing the age relations of three dikes of different composition in Corbaley Canyon. Scale: 1 inch = 60 feet.

contact exhibited by the dikes differs widely depending upon the character of the intruding magma. In general it was found that the lamprophyres have very irregular contacts and cause great alteration in the gneiss which they cut across, thus indicating that they were exceptionally fluid at the time of injection. The magma apparently became more viscous as it became progressively more acidic, for the walls of the dikes become increasingly straighter and more regular until in the highly quartzose types the contacts are very straight and clean cut.

The contacts exhibited by some of the more basic dikes indicate

that they must have possessed exceptional fluidity. Individual dikes will often vary considerably in width when followed along their strikes. Thin streamers and apophyses from the dike penetrate the gneiss in every direction, extensively metamorphosing it as they go. These stringers are often only 1 or 2 inches wide, yet they penetrate into the gneiss distances of 20 feet or even more. Variations in composition from the parent-dike can be noted in almost any of these apophyses. In the field several apophyses about 2 inches wide can be noticed to vary in a few feet from a very black basic rock to stringers of a light-gray shade containing hardly any mafics. In general the apophyses appear to be somewhat more acidic than the parent-dikes. Some of the apophyses also vary from their parent-bodies in the kind of minerals that they contain. One apophysis from a hornblende-bearing rock had principally biotite in place of hornblende. Changes in the type of feldspar were also noted. In one case a thin section of an apophysis showed it to contain sphene to the amount of 4 or 5 per cent of the rock, while thin sections taken from the parent-dike failed to show any sphene whatever. Quartz and micropegmatite are often present in considerable amount in the apophyses, although they occur only rarely in the main dike. Variations in composition of the more basic dikes at different points along their strike have also been observed. These variations are usually not so marked as those noted in the apophyses.

Variations in composition within the same rock body in the lamprophyric magmas have been noted from several districts. In the Coeur D'Alene mining district of Idaho lamprophyric dikes have been described which vary along their strike from spessartite to minette in a distance of only 100 yards.[1] David Williams,[2] in a description of the Cronkley mica lamprophyres of North England, notes at length that some of the dikes have acid segregations or "blebs" which are thought to have been derived from differentiation in the magma basin in which the lamprophyres were formed.

The increasing viscosity of the successively more acidic dikes is

[1] Earl V. Shannon, "Petrography of Some Lamprophyric Dike Rocks of the Coeur D'Alene Mining District, Idaho," *Proceedings of the U.S. Nat. Museum*, Vol. LVII, p. 480, 1920.

[2] David Williams, "The Cronkley Mica Lamprophyres," *Proceedings of the Liverpool Geological Society*, Vol. XIII, Part IV. (1923), p. 331.

easily apparent in the field. Figure 3 shows the relations at a point in the upper part of the canyon where the increasing viscosity of the more acid dikes may be seen by the irregularity of the contacts of the three dikes shown. The most acidic dikes represented in Corbaley Canyon are granophyres containing much phenocrystic quartz. In their extreme viscosity they stand in direct antithesis to the peculiar physical condition of the lamprophyric magmas. These dikes were so viscous that they appear to have oozed up along fractures in approximately the same condition as thick pitch. They show absolutely clean-cut walls exhibiting no contact metamorphism. The mineralogical analysis indicates that these dikes were rather high in volatile matter, but their highly siliceous character and probably rather low temperatures were the reason for their viscosity.

The contact relations of a spherulitic granophyre dike outcropping at the edge of the Sunset Highway 400 feet below Camp Beaver Den, in the central part of Corbaley Canyon, are of especial interest in this connection. At the point where the granophyre joins the highway it is cutting the Ribbon gneiss. On account of its greater resistance to weathering it stands up as a wall as it continues on up the canyon side. About 200 feet from the highway it cuts across a 25-foot kersantite dike and across the amphibolites derived from the contact metamorphism of the kersantite. Both sides of the granophyre show peculiar grooves and striations throughout practically the entire length of its outcrop, producing the appearance of rough, unpolished slickensides. The direction of movement, as shown by the slickensides on both sides of the dike, is the same as the direction taken by the intruding magma. That the striations were caused contemporaneously with the intrusion of the dike is proved by the fact that *where the granophyre truncates the kersantite an angular fragment of the kersantite was found actually frozen into the granophyre, while a long trail behind it shows where the granophyre moved past before it finally froze fast.* Thin sections revealing the glassy contact of the dike around the kersantite fragment are considered proof that the movement occurred at a time when the dike was still fluid enough finally to freeze around the fragment, but was viscous enough so that the scratches made by the fragment were preserved when the

magma completely solidified. The supposition that faulting along the sides of the dike when the magma was almost solidified caused the striations and chatter marks is disproved by the fact that these features appear on both sides of the dike and indicate that it moved upward in reference to both walls. This relationship is also substantiated by the fact that other dikes which the granophyre cuts are not displaced except through the opening of the fissure which it fills. The only assumption that seems tenable with the facts is that the granophyric dike was actually so viscous that it scratched its sides against projecting particles on the walls of the fissure which it intruded.

CONCLUSIONS

The evidence presented above seems to the writer clearly indicative that the dike rocks in Corbaley Canyon represent simply a series of samples drawn off at intervals during the complete differentiation of an original magma of lamprophyric composition. That an intermediate or a granitic magma did not split into complementary lamprophyric and aplitic poles, as has been thought to be the most plausible hypothesis as to the origin of lamprophyric dikes in other regions, is proved by the fact that the dike rocks of intermediate and granitic composition in the canyon are in all cases younger than the lamprophyres. The lamprophyric dikes were found in all cases to be the oldest unmetamorphosed intrusive igneous rocks in the district.

If a magma of the composition of the lamprophyres in Corbaley Canyon were cooled fairly slowly in some intercrustal basin, differentiation might be expected to proceed with greater ease and rapidity than in any other type of magma. The excessive amounts of volatile constituents as well as the basic composition of the rock would render the magma exceptionally mobile and thus furnish especially excellent conditions for the rapid diffusion of molecules in the melt, which would hasten the segregation of these molecules together to form crystals. Crystals of different specific gravity from that of the magma from which they separated out could rapidly rise or sink in the magma because of its extremely low viscosity.

As differentiation went on, the increasingly more siliceous rocks developed would be expected to be more viscous, owing to the fact

that they are cooler and owing also to their more siliceous character. They ought still to contain large amounts of volatile matter which would increase their mobility to some extent, but it is probable that the effect of the volatile matter is used up in keeping the mass fluid at its lower temperature.

Whether or not the lamprophyric magma from which the differentiates was formed is itself a differentiate of some other igneous rock body is problematical. The older igneous rocks in the immediate district have undergone extreme dynamic metamorphism and clearly belong to a much older period of vulcanism than the dikes which intrude them. The nearest igneous rock body that has not suffered severe dynamic metamorphism and is at the same time older than the Tertiary lavas and intrusives is the Mount Stuart Batholith, which lies about 20 miles to the southwest. This batholith has given rise to great multitudes of offshoot dikes along its borders, and it is thought highly possible that the intrusions in Corbaley Canyon may represent differentiates from some wet, basic offshoot of the Mount Stuart Mass.

OBSERVATIONS ON SOME DETAILS OF WAVE EROSION: WAVE FURROWS AND SHORE POTHOLES

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ABSTRACT

The wave-formed furrows and potholes near Moss Beach, Calif., occur as the result of (1) the contraposed shore line; (2) the relative freedom of that coast during certain seasons from severe storms, which produce violent waves; and (3) the abundance of tool materials which are very tough compared with the furrowed and potholed rock. The conclusion is drawn that the aggregate activity of small wave erosion, lost sight of in the startling effects of violent wave work, may be of great importance especially in regions of low storm frequency.

INTRODUCTION

The discussion of the mechanical work of waves in most treatises on shore erosion is confined to the effects produced in time of storm. Little is found of the prolonged effect of the ordinary wave. Undoubtedly the emphasis on storm conditions is well placed in so far as the amount of work accomplished for a given period is concerned. However, on some coasts severe storms are infrequent, on others storms are seasonal in occurrence. Even on stormy coasts the intervals between storms cannot be considered as characterized by erosional inactivity. The aggregate effectiveness of what may be called the "modal" or "calm-weather" wave appears to be of considerable importance.

Opportunity to observe a limited portion of the California coast furnished the writer with illustrations of some of the special means by which the calm-weather waves accomplish work.

WAVE FURROWS

As the water from broken oscillatory waves washes up the shore, its momentum causes it to proceed without much regard for slight inequalities of surface relief. The sand and fine gravel washed with it soon detect the zones of weakness in the exposed rock surfaces. An effective etching process is set at work which develops

in one place ramifying grooves along intersecting joints; in other places deeper channels or furrows where converging or parallel joints determine a larger zone of weakness.

The wash, receding under gravitational force, and controlled therefore, to a greater extent than when advancing, by the slight inequalities of surface, carries its abrasive sand and gravel along the etched zones. Hence the process once started proceeds with a certain degree of acceleration.

Such a process depends for its effectiveness upon the activity of waves of limited violence. Too great velocity and agitation of the water fail to concentrate the abrasive material.

FIG. 1.—Wave furrow at ebb tide

Wave furrowing on a glaciated shore line might well accentuate striae or grooves. The two kinds of phenomena might also be confused.

SHORE POTHOLES

Fragments of rock detached by weathering from sea cliffs, or remnants from immediately overlying layers, if too large and heavy to be moved any distance by the ordinary waves and breakers, may be churned about sufficiently to wear away the rock immediately beneath them. The result is the formation of shore potholes of essentially the same type as the river pothole. This is in contrast to the process of which Geikie writes: "The blows dealt against shore-cliffs by boulders, gravel, and sand swung forward by breakers were aptly compared by Playfair to a kind of artillery."[1]

So far as the writer is aware, little has been published on this phase of wave work. Lahee[2] mentions the possibility of shore-line

[1] A. Geikie, *Text Book of Geology* (4th ed.; London, 1903), Vol. I, p. 569.

[2] F. H. Lahee, *Field Geology* (New York, 1916), p. 31.

potholes, while Elston[1] in a paper on potholes refers to Henkel on the occurrence of pothole-like depressions near Fort Renfrew, British Columbia, on the west coast of Vancouver Island.

W. H. Shideler informs the writer of the occurrence at La Jolla, California, of shore-line potholes in a conglomeratic sandstone.

SPECIAL CONDITIONS FAVORABLE TO THE DEVELOPMENT OF FURROWS AND SHORE POTHOLES AT MOSS BEACH, CALIFORNIA

At Moss Beach, California, about thirty-five miles south of San Francisco, the conditions of the local geology are such as to favor

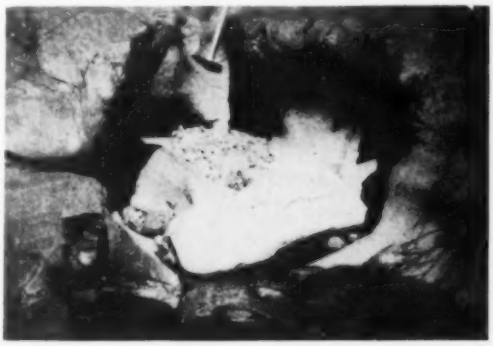

FIG. 2.—Wave furrow and pothole-like depression

the development of the features noted above, especially the potholes. The high-tide level approximates in many places the unconformable contact of the Merced (Pliocene) formation and the more recent (Quaternary) sands.[2] A low sea cliff has been developed in these sands, leaving a nearly flat terrace on the top of the older and more resistant beds against which sea erosion is making slower headway than against the overlying sands. In other words, the shore line is the type for which Clapp[3] has suggested the term "contraposed."

[1] E. D. Elston, "Potholes, Their Variety, Origin and Significance," *Scientific Monthly*, Vol. V (1917), pp. 554–67; Vol. VI (1918), pp. 37–51.

[2] A. C. Lawson, *U.S. Geol. Survey Geologic Atlas, San Francisco Folio* (1914), No. 193.

[3] Charles H. Clapp, "Contraposed Shorelines," *Journal of Geology*, Vol. XXI (1913), pp. 537–40.

The Merced formation, as exposed along the Moss Beach shore, consists of a variable series of gray, gray-blue, and gray-buff shales and sandstones, with at least two beds of conglomerates composed of rounded, granitoid gneiss bowlders which range in size from a half-foot to as much as four feet in diameter. The series dips, in general, seaward (southwest) from 15° to 20°, and is displayed in a series of gentle, seaward-pitching folds.

In places the bowlders, weathered free from the shaly matrix of the conglomeratic beds, occur in considerable abundance. Wave-wash, churning these gneissic bowlders on the shale, has caused the

FIG. 3.—Contraposed shoreline near Moss Beach. The foreground shows the exposed top of one bowlder bed. In the middle ground and distance the residuals of a higher bowlder bed are shown. At the upper right is the mantle of sands.

excavation of the potholes. The washing of the sand cliffs and the slow disintegration of the gneiss fragments furnished the abrasive for the etching of the furrows. The effectiveness of these processes is furthered at Moss Beach by the relatively flat upper surface of the basement of the contraposed shore line. The recession of the mantle has left a cleared terrace over which even the ordinary wave develops a considerable wash current.

For convenience in description the term "molar" will be applied to the bowlders and fragments which are the tools instrumental in grinding out the potholes.

The permanence of the molars is dependent upon (1) the contrast in the hardness between the molars and the shale, and (2)

the size of the bowlders, which insures their remaining in the potholes and even in the small initial depressions in all wave activity except, perhaps, the most severe.

A few of the bowlders were fragments of the sandy phases of the Merced formation, but the large majority of the molars were com-

FIG. 4.—Shoreline potholes

FIG. 5.—Shoreline potholes

posed of tough granitoid gneiss. That their size, relative to wave activity, was sufficient to preclude their traveling is indicated by the growth of seaweed on the upper surface of several of the bowlders. One of these may be seen in Figure 4.

Another important factor in the genesis of the potholes is the relative freedom of the California coast from severe storms for

quite long periods of time. Such a situation permits the bowlders to be jostled in the wave-wash without being carried away. The storm frequency along the coast near Moss Beach may be deduced from the pilot charts of the North Pacific Ocean published by the United States Hydrographic Office. For the five-minute rectangle bounded by 120° W. to 125° W. and 35° N. to 40° N., the percentage of winds of force 8 or over (or gales; Beaufort scale, 8 = 39–46 mi. per hour) is given in Table I. For comparison with the frequency of gales, Table I also shows an analysis of the wind roses for the same rectangle for calms and wind force. Most of the data on the charts of the North

FIG. 6.—Shoreline potholes in process of formation. Same potholes as Fig. 4

Pacific Ocean are summarized from observations during the eleven-year period 1897 to 1907 inclusive.

A brief study of Table I will suffice to show that for parts of the year the Pacific Ocean off the coast near Moss Beach is affected by slightly more than one storm hour per hundred hours, while the average force of the winds is less than 13 miles per hour (4 on the Beaufort Scale) for the whole year. It is also notable that from September to December (inclusive) the percentage of calms is over 20. In December the number of calms is 38 out of 100 observations. In the same area the percentage of gales for December is 1; while the 62 observations showing wind give an average force of less than 13 miles per hour.

For the sake of comparison, similar figures are cited for a proverbially stormy coast—that off Halifax.

A glance at Table III shows how well the Pacific Ocean deserves its name! From the figures cited the North Atlantic would appear to have four times as many stormy hours as the North Pacific in the areas compared.

TABLE I

STORM FREQUENCY FOR PACIFIC OCEAN NEAR MOSS BEACH; ANALYSIS OF WIND ROSES

120° W. to 125° W., 35° N. to 40° N.
Showing Percentage of Gales, Calms, and Force of Wind (Beaufort Scale) on All Points

Month	Gales: Percentage Winds of Force 8 or More	Calms: Percentage Calms, Variable and Light Winds	"Average"* Wind Force
January	3	11	3.50
February	5	16	3.67
March	3	17	4.00
April	2	20	3.40
May	4	13	4.00
June	3	11	3.83
July	2	15	3.80
August	(1)	(18)†	(3.40)
September	2	24	3.00
October	1	21	2.83
November	2	22	2.43
December	1	38	3.33
Average	2.55	18.91†	3.44†

* The Beaufort Scale does not lend itself well to averaging since the numbers do not represent a regular progression in velocities. Averages are used in the present figures since the numbers are uniformly small and because some composite figure is necessary.

† The pilot chart for August, 1925, does not carry a wind rose for this five-minute rectangle. The values in parentheses are interpolated and are not included in the averages at the foot of the columns.

If Moss Beach were to experience the storminess of the Atlantic Coast it is doubtful if the potholes would endure. The violence of the activity would soon cause the tough bowlders to grind away the walls which, under existing conditions, are adequate to confine them. No new potholes would form, for the breakers would move the bowlders too far and too violently.

The potholes seem so nearly identical with similar holes of undoubted fluvial origin that the writer was led to consider the possibility of the existence of a "fossil" river channel of post-Merced

erosion time. Such a hypothesis had to be dismissed for the reason that the limited distribution of the potholes does not conform to the depressed portions of the unconformity, whereas the layers of the

TABLE II

STORM FREQUENCY FOR ATLANTIC OCEAN OFF HALIFAX; ANALYSIS OF WIND ROSES

60° W. to 65° W., 40° N. to 45° N.

Showing Percentage of Gales, Calms, and Force of Wind (Beaufort Scale) on All Points

Month	Gales: Percentage Winds of Force 8 or More	Calms: Percentage Calms, Variable and Light Winds	"Average"* Wind Force
January	17	4	5.0
February	23	4	4.9
March	18	6	4.4
April	12	7	4.4
May	4	10	4.0
June	3	8	4.25
July	2	14	3.5
August	2	11	3.25
September	4	7	4.0
October	8	7	4.25
November	13	4	4.25
December	18	5	4.0
Average	10.33	7.25	4.18

* See first note to Table I.

TABLE III

COMPARISON OF PORTIONS OF NORTH PACIFIC COAST WITH NORTH ATLANTIC COAST WITH REGARD TO GALES, CALMS, AVERAGE WIND FORCE

	Pacific	Atlantic
Monthly average percentage, gales	2.55	10.33
Monthly average percentage, calms	18.9	7.25
Maximum percentage, gales, one month	5 (Feb.)	23 (Feb.)
Maximum percentage, calms, one month	38 (Dec.)	14 (July)
"Average"* wind force, Beaufort Scale on all points on which wind blows	3.44	4.18

* See first note to Table I.

sands above the erosion break show clearly that the now depressed parts of the unconformity were likewise depressed at the time of the sand deposition.

The coincidence of conditions which appear to favor the special development at the Moss Beach locality of the potholes and furrows are: (1) the presence of the unconformity between the slightly consolidated and the compact rock series which permitted the sweeping clear of a relatively large and flat terrace, that is, the contraposed character of the shore line; (2) the relatively small number of periods of high waves especially during certain seasons; (3) the presence of the weak shale layers; (4) the abundance of tools for the water to actuate: in the case of the furrows, the sand; in the case of the potholes, the resistant fragments and bowlders too large to be more than jostled by the ordinary wave.

SUMMARY AND CONCLUSIONS

Wave erosion, like river and wind work, is most effective and visibly striking when activity is violent. But like other physiographic agents producing seemingly insignificant change, the calm-weather wave erosion is effective in the aggregate.

Shore-line furrows and potholes are details which are characteristic of the activity of the waves when not violent enough to overcome the effect of gravity in holding the tool materials against the rock floor. This situation probably occurs in many places. But only where other conditions are present, as at the Moss Beach locality, are the results significant enough to force themselves on one's attention.

The erosive work of the ocean has been compared with the cutting of a great horizontal saw. If the analogy be continued, the foregoing study of details emphasizes that the teeth of the saw are, at times, directed downward under the force of gravity and that the kerf widens from the top.

EVIDENCE OF ASSIMILATION AND ASSIMILATION PROCESSES

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ABSTRACT

This note is contributed to the criticisms, published in the October–November, 1926, number of the *Journal of Geology*, which have grown out of an earlier article by Mr. George W. Bain. Mr. Bain advanced arguments for the apparent disappearance of over 10,000 feet of sediments, which he attributed to the intrusion of the Sudbury norite. Bain's understanding of the stratigraphy of the district seems to be at fault according to the work of the present writer which was quoted by Bain to support his own views.

Mr. George W. Bain has recently quoted my writing to support his conclusion that the Sudbury sill has assimilated vast quantities of Huronian sediments. He has quoted my report on the Wanapitei[1] area for the thicknesses of the Bruce series, and of the Gowganda and Trout Lake formations. If Bain had followed my report more closely I think his idea of the geology of the district concerned would have been somewhat different. He concluded that the presence of the Wanapitei quartzite beneath the Sudbury sill implies the absence of all the Huronian, and he explained by assimilation the consequent absence of the Huronian to the extent of 10,000 stratigraphic feet; whereas the Wanapitei quartzite is really part of the Bruce series, and its presence indicates that the Huronian rocks have not been assimilated to that extent. On page 34D of the report which Mr. Bain has quoted, I have written as follows:

> The main results of the season's work are: a corrected geographical and geological map; additional knowledge in regard to the ore deposits; and the elimination of the type occurrence of Wanapitei quartzite from the Sudburian series and its recognition as part of the Mississagi formation of the Bruce series.

Page 39D reads as follows:

> BRUCE SERIES
>
> MISSISSAGI FORMATION
>
> The contact between the base of the Huronian series and the underlying schists and granite is exposed in very few places, but opposite the diabase point

[1] *Summ. Report Can. Geol. Survey*, 1921, D, p. 38.

in Bowland bay may be seen the unconformable contact between a basal conglomerate and an underlying body of schists which contains an intrusion of acid rock. The contact follows close to the shore for nearly 3 miles, but the relations are obscured by intrusions of diabase, and by high water. This conglomerate may well be part of the basic conglomerate of the Mississagi formation. . . . .

Above the conglomerate, which is less than 50 feet thick, is a thick quartzite member which is most probably from 3,000 to 5,000 feet thick. The quartzite, very well exposed on the east side of Bowland bay, runs with diabase interruptions to Southeast bay by way of Howie and Oak islands both of which give excellent exposures, and continues to the north of the Indian reserve, composing most of the peninsula and the islands between Bowland bay and Outlet bay. It outcrops again from Outlet bay to Southeast bay, and upon Ashganing lake, and thence passes to the southeast beyond the borders of the area.

Inasmuch as the conglomerate member and the quartzite are together correlated in this report with the Mississagi formation as described by Collins,[1] whereas Coleman[2] called this quartzite the Wanapetei quartzite and placed it in the pre-Huronian, Sudbury series, it is deemed advisable to describe in detail some of the exposures of these rocks.

On the west side of Massey bay, lot VIII, concession IV, syenite rock intrudes greenstone schists containing many smoky quartz veins, and both are overlain unconformably by a basal conglomerate, here correlated with the Mississagi formation.

The main contribution of my report is the correlation of the Wanapitei quartzite with the Mississagi quartzite, in support of previous work done by W. H. Collins. Although a person is generally gratified to find that some of his publications are being read by other people, nearly everybody dislikes having partial quotations made in such a way as to contradict the most important conclusions concerned. The presence of the Wanapitei quartzite beneath the Sudbury sill would indicate definitely that all the Huronian series had not been absent at the time immediately following the intrusion.

Furthermore if Bain would refer to *Geological Survey of Canada Publication No. 1948*, Wanapitei lake map area, Sudbury district, Ontario, and compare the treatment of that area as indicated on the map with statements in the test, he would note a basal conglomerate of the Bruce series (beneath the Wanapitei quartzite) carefully described on page 39D which is not overlain by the Sudbury sill. The

[1] W. H. Collins, *Geol. Surv., Can., Mus. Bull. No. 8*, 1914.

[2] A. P. Coleman, *Ont. Bureau of Mines, Ann. Rept.*, Vol. XXIII, Part 1 (1914), pp. 213–14.

east edge of the Sudbury sill in Capreol township lies upon pre-Huronian granite. So far as our evidence goes *in this place* the Mississagi, or the Wanapitei quartzite, which are one and the same thing, may not have been present at all in this place where the Sudbury sill is now found. For information concerning distribution of the Huronian rocks throughout the western part of the Sudbury basin, readers may consult the works of Coleman, Knight, and Collins, but as far as Wanapitei lake area is concerned, which has been particularly referred to by Bain, in my judgment there is almost nothing in the stratigraphy to support Bain's arguments in favor of assimilation; on the contrary the likelihood of a plane of unconformity beneath the Trout Lake conglomerate now occupied by the Sudbury norite, as suggested long ago by Coleman, seems highly probable from the field evidence in Capreol township.

RESEARCH IN SEDIMENTATION

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The fundamental factors in sedimentation may be placed in three groups: (1) the original materials and their modifications to become sediments; (2) the environments through which the sediments are transported and the environments in which deposition occurs; (3) the processes responsible for deposition and transportation, and the processes operating from the time of deposition to consolidation. On rigorous analysis these factors may be reduced to two: sources of materials and environments, as the processes in most instances are resultants of, or are strongly modified by, the environment. However, for purposes of discussion it seems best to divide the consideration into source rocks of sediments, methods of production (breaking down of the source rocks), environments, processes, products, and changes subsequent to deposition.

1. *Source rocks of sediments.*—These are fairly well known for the igneous rocks, and the field seems adequately manned. The sedimentary rocks are less well known, and there is room for many workers in their study. Such study, to attain fullest results, should be undertaken by students who are well informed on modern sediments and the principles of sedimentation.

2. *Methods of production of sediments.*—This entire field should be reinvestigated, and series of studies of rock destruction under many environments should be undertaken. Particularly should there be considered the factor of micro-organisms in rock destruction. Too little is known of the actual details of the breaking down of rocks, and there is so much tradition in the current statements that one is not certain as to their exactness and in many instances even of the very existence of the phenomena stated. The statement of the prevalence of one method recently has been challenged by Blackwelder. Several students in different parts of the United States and Canada should devote time for some years to the study of the

actual processes of rock destruction. These studies should be so located that a wide range of environments over a wide range of rocks is represented. The students should be so equipped by training as to be fully able to appreciate the physical, chemical, and biologic factors involved. The students should carefully distinguish rock breaking, or physical breaking, from rock rotting, or breaking up through chemical processes. It is desired to learn how rock destruction proceeds and what are the results. When this information has been obtained with careful detail, sedimentationists will be in a position to interpret more accurately the results as found in the geologic column. In order to have the work proceed in systematic fashion, the students should be selected and assigned to territory. This could hardly be done were the work not subsidized.

3. *Environment.*—As noted above, environment is of fundamental importance in sedimentation. It is divisible into the environments of the source materials, the environments through which the sediments are transported, and the environments in which deposition occurs. The three may be the same, and they may be as different as the range of environments of the earth permits. The environments of the source materials should be investigated in connection with the processes and results of rock destruction. The environments through which the rock particles move from the places of production to the places of deposition should be studied for the purpose of learning what changes are produced as a consequence of these. In this consideration it is difficult to divorce the consideration of the processes from the environment, and it seems best to consider them together. However, some of the processes do not change with certain features of the environment.

To be specific, a fine problem in this connection would be studies of the sediment changes occurring in the Mississippi River system. The losses and gains in silica, potash, etc., should be studied as the waters pass from one environment to another or are influenced by waters entering from a tributary which have been modified by the environment of the tributary. Not only should it be learned what are the losses and gains, but it should also be learned what are the factors responsible for the changes.

Were studies of this character made for streams of the several

environments as represented by the region of the Rio Grande; by the Missouri, Ohio, and Upper Mississippi system and the results after mingling in the water of the Lower Mississippi; the Yukon system; and one draining such a vegetation-covered region as Labrador, Hudson Bay slope, or any vegetation-covered region where large contributions are not made by glaciers, it seems certain that important results would be obtained. Studies of streams of tropical environments should also be made. This problem has bearings on other phases of geology. The deposition of iron and silica and thence of the pre-Cambrian iron formations might receive some simplification from its being done. The task is no small one, and it is probable that many years will pass before it is completed for several of the more important environments; but its difficulty should be no reason for delaying its beginning.

It is probable that the impress on sediments of the environment of deposition is greater than the impress either of the environment of origin or that of the environments through which the sediments are transported. That this is the case in some instances seems very certain, but in many instances the assumption rests on no body of definitely ascertained facts. Speaking generally, very little actually is known of the effects of the environment of deposition, either with respect to the types of sediments deposited, the rates of deposition, or the effects impressed upon the sediments. This is obvious from the various discussions relating to the places of origin of such common sedimentary products as the limestones, black shales, coals, etc. Very few careful studies have actually been made of the relations between environment and the resulting sediments, and, in my judgment, here is one of the weakest places in the sedimentary armor. Moreover, many of the studies which have been made have not been sufficiently detailed and inclusive to obtain all the essentials.

Every site of deposition gives a certain range of environment—the deep sea environment may be the one exception in which conditions are essentially uniform over a wide area. Very small factors, apparently trivial, may fundamentally change floras and faunas and entirely change the type of sediment deposited. It is felt that this fact is not generally appreciated. There are very few places where men dwell that do not offer opportunities for studies of the

environmental factor in the deposition of sediments, and every such study would be a contribution. Studies similar to those made by Kindle on Lake Ontario, Collet on Lake Geneva, and Vaughan and his associates in some of the tropical waters are illustrations. White has proposed studies of the waters of the Caribbean region, and I know of no better place, as it is a region of striking depth contrast and varied wave and current action, thus giving a wide range of the environmental factor. Studies of the Caribbean call for large funds which do not seem to be available, and studies on the extensive scale proposed may not materialize—no excuse, however, for not attempting to make the work materialize. However, studies of a similar character but on a smaller scale could be made in scores of places about many of the embayments of our coasts. A region which would give splendid results is the Gulf of St. Lawrence. It is a body of water with some places of strong wave and current action and other places with waters comparatively quiet. There is a wide variation in the distribution and abundance of its plant and animal life. There are places where the bottom is scoured to considerable depths and other places where sediments are accumulating in shallow waters. The waters in some places are normally salty and in others are fresh. There are all transitions between. The salinity also shows a range over considerable areas. One or several students might devote vacations to studies of these waters for many years, and the studies could be made at small annual expense. The work, if several students were concerned, should be co-ordinated. It should begin at a selected place, or places, and should include studies of the floras and faunas, the environment, the processes, rates of deposition, the products, the rocks of the coasts, the contributions of the streams, and the relations of the various factors. I think the fishermen would be glad to co-operate, although tourist travel in the St. Lawrence is increasing and the fishermen are less willing to help than in the past. The equipment should consist of an outboard motor boat, sounding and supplementary apparatus, and camp equipment. As the work was completed at one place, progress could be made outward therefrom and along the shore. For one student it would be vacation work of many years, but a work pregnant with great possibilities regarding sedimentation. Collections could be worked up

during the winter, and much of the material might be turned over to graduate and advanced students.

One of the finest places known to me for studies of this nature is the Gulf of Finland and east Baltic. The range of sediments in these waters is wide, the fauna is a modified one, the tidal range is small, there probably is little scouring of the bottom, and the level of no deposition must be close to the surface. Studies of the sediments of these waters would yield data which might be of great importance to the geology of oil as there are considerable areas where organic materials are being deposited.

The many lakes of the United States and Canada offer extremely important fields for study. Hardly any two are alike, and there is hence a wide range of environments. Many lakes have been studied intensively from the points of view of their faunas and floras and the factors upon which these depend, but little is known of these lakes from the point of view of their sediments. The biologic studies, however, afford excellent foundations upon which to base sedimentary studies.

Every river system affords fine problems for the study of its sediments and their creating conditions. The study of the sediments of the White River of Arkansas and Missouri, as projected by Littlefield of the University of Iowa, is a type of study which ought to be carried through for many rivers. Too few studies of this kind have been made, with the result that too many of our ideas relating to fluvial deposits are mere generalizations of doubtful correctness.

Little is known of the sediments of Arctic waters, and in these days of Arctic exploration a properly equipped geologist should be on the staff of each expedition.

Problems from the point of view of the environment are almost limitless in number, and all that is essential is the selection of areas from which the largest volume of data might be secured.

4. *Transportation processes.*—The several methods of transportation are believed to impress certain characteristics upon the sediments carried. Some of these characteristics are believed to be known, and the stated development of other characteristics seems to rest on assumption and the authority of tradition. Some work has

been done, and considerable is being done in an incidental way in several laboratories. More systematic results would be obtained could suitable students be selected and subsidized, with directions for working on certain problems. I have in mind work similar to that done by Wentworth on the larger rock particles.

5. *Products.*—Here are scores of problems. The committees connected with research related to oil geology seem to be taking care of the sedimentary products related to oil. The studies connected with coal seem to be well taken care of except that there seem to be few or no investigations of the initial stages of coal sedimentation, particularly the processes of metamorphism of peat bogs and other sediments in which the vegetal contributions are large. Studies ought to be made of the biochemistry of vegetal accumulations, the changes from the surface downward, and the depths to which biochemical metamorphism extends. The origin of dolomite is not yet known. The solution of this problem may be attained by one who is in a position to make wide field studies, who is trained in chemistry to understand the relations there involved, and who has the ingenuity and imagination to construct apparatus whereby dolomite may be produced under conditions which exist in nature. The explanations evolved should also show why a given formation is dolomite in one region and calcite limestone in another; why the Richmond formation is dolomitic in Wisconsin and calcite limestone in the Gulf of St. Lawrence and the Russian Baltic.

The origin of such vast deposits of iron minerals and associated materials as are found in the pre-Cambrian is not yet settled. Several hypotheses are extant, and it should be possible to test some of these were the postulated environments sought or created. Gruner suggests algae and micro-organisms as partly responsible agents, but Hawley has produced structures similar to those identified by Gruner as organic. The subsidizing of a well-selected student might yield results of fundamental importance were he turned loose on this problem with adequate funds for collection and preparation of material and for experimental study.

The conditions of deposition of phosphorites, such as those of the Rocky Mountain region, are yet unknown; and a little money spent

on this problem might yield important results. These results might have other bearings.

A monographic study of flint, chert, and related rocks would yield important data. Tarr has made an extensive study of these products as they occur in Missouri and neighboring states, but to make his results of general application he should have opportunity to study the chert and flint deposits of the geologic column, should study deposits of the same age and same general character as those containing the chert which are without these materials, seek for environments in the present seas in which are being deposited materials like those in which the chert is found, study cases of weathering where chert is said to be in process of formation, and attempt the production of chert by artificial methods. The explanations reached should not only show why chert is in the Niagara limestone of the upper Mississippi Valley (for example), but why it is not in limestone of the same age in the St. Lawrence region.

The origin of oölites is not yet solved. Many theories have been proposed, and no decision seems to have been reached for any one of them. I have a few calcareous oölites of artificial production, but the facts underlying their production are not yet known. It should be possible to duplicate the conditions in nature under which oölites are formed and learn the facts of the matter. A good place to carry on experimental work on the origin of calcareous oölites is in the University of Utah, as it is near waters in which there is abundant oölite in formation.

It is not worth while to go into details with respect to other products, as there is hardly a substance whose study will not yield results of importance.

6. *Changes subsequent to deposition.*—Little is known on this score. One hears much of diagenesis and it is a fashionable word, but little is known of its occurrence. Various formulas have been suggested for the changes occurring in sediments after their deposition, but these rest on few or no observational data. The metamorphism of a peat bog or other vegetal deposit might be a part of this investigation. Some geologists have stated that the materials of limestone, not determinately organic, are really of organic origin

but that the organic structures have been destroyed by diagenesis. One wonders. It is possible to attack this problem in many places. Every peat bog is an experimental laboratory. Every marl bed of any lake would yield data of importance. The shell beds of modern seas are readily accessible in many places. One should not need to suggest problems along this line, as every recent deposit will give information of value.

Summary.—On the foregoing pages I have called attention to some problems of a more general character, and I have referred to several problems in a specific way. I consider studies of the several environments as the most pressing need and those from which the most fruitful results are likely to be obtained. Sedimentation needs great study of modern sediments in connection with the environments in which these sediments are deposited. When sedimentationists are adequately equipped with an understanding of the relations between sediments and environments, they will be in a position to more intelligently attack the problems connected with the sediments of the geologic column. In any and every problem it is probable that its various ramifications will lead the adequately prepared and adequately mentally equipped student to consideration of many factors beyond the immediate scope of the matter studied.

REVIEWS

Geology Manual. By Richard M. Field. Princeton University Press, 1926. Pp. 132; 17 plates.

Professor Field, as instructor in charge of the introductory course, Geology 201, at Princeton, has compiled in book form a manual for the purpose of standardizing laboratory instruction. In his preface the author writes: "There appears to be no standard in the teaching of Geology such as exists, to a certain extent at least, in the teaching of Chemistry and Physics." In an attempt to remedy this situation the Princeton standard is offered for general use. Doubtless if this standard were established throughout our educational institutions the level of geological instruction would be raised in many of them.

The book is attractive in form and typography, and shows care in preparation as well as in execution. Blank pages for the writing of exercises and quadrille ruled sheets for the plotting of profiles are bound in, perforated on the margin so that they may be torn out and handed in for correction.

Errors and departures from common usage are few. One might question certain items. For example (p. 32): When the texture of an even-grained clastic sediment is indistinguishable is it safe even for an elementary student to call it "colloidal?" There appears to the reviewer to be one serious omission in the map studies. Are not the topographic effects of volcanism of as much interest and importance as braided streams and tied islands?

The treatment of geological structures is limited to the study of blocks and structure sections given in the *Manual.* To the reviewer it would seem preferable to turn the attention of the student from these idealized illustrations to the actual influence of structures on topography, so well represented by such quadrangles as Tyrone, Pennsylvania, and Ballarat, California-Nevada.

For the teacher who wishes to have for laboratory purposes a stiff outline which includes material in rock-forming minerals, rocks, topographic expressions, and structural relations, the *Manual* is reasonably adequate. On the other hand, the tone of the book is distinctly conservative. To the reviewer it does not seem to reach beyond the pattern set by

the standard text of two decades ago. There is little which reflects the great recent progress of the science. Although it is true that much of the new is not suitable for the elementary laboratory, it is unfortunate to leave too much of it for lecture treatment.

The book also raises the question in the reviewer's mind as to the value of the kind of course which the Princeton *Manual* reflects. The mass of detail on rocks and rock-forming minerals and on physiography indicates that the course is planned primarily for the students who may concentrate in geology. The remaining students who are in the course for any one of a number of more or less significant reasons may reap the reward of workman-like distinctions between phenocryst and metacryst while they absorb quite casually the cultural and scientific value of the subject. From the point of view of these students both the *Manual* and the course are misnamed. The former might well be called "Manual of Physical Geology," while the latter is a course in the same field. It is not an "introduction" to anything except a phase of the subject. No mention is made of the paleontological side or of the exceedingly pertinent economic phases of the subject, both of which should undoubtedly be included if the course or the *Manual* is a true introduction to geology.

In elementary courses of the Princeton type an opportunity may be lost to make geology a subject of broad interest as part of education. An academic question of long standing is thus raised regarding the merits of a survey of the whole field (usually criticized for dilettantism) and the detailed treatment of a limited portion of the field (usually justified on the grounds of thoroughness). It is apparent that the Princeton standard, as edited by Mr. Field, is firmly committed to the disciplinary side.

A. C. SWINNERTON

Index to the Mineral Resources of Alabama. By WALTER B. JONES. *Bulletin 28, Geological Survey of Alabama,* 1926. Pp. 250.

An illustrated summary of the mineral resources of the state.